REPORT No. 65

THE KILN DRYING OF WOODS
FOR AIRPLANES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

PREPRINT FROM FIFTH ANNUAL REPORT

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FOREWORD.

This publication is one of a series of eight monographs prepared by the Forest Products Laboratory of the Forest Service, United States Department of Agriculture, for publication by the National Advisory Committee for Aeronautics.

The purpose of the series of monographs is to discuss in detail the various requirements of wood for use in aircraft, and also to make public some of the results obtained in the experimental and testing work of the Forest Products Laboratory undertaken for the Army and Navy during the war.

The subjects discussed in the series will include: (1) Kiln drying of airplane woods, (2) the effect of kiln drying on strength, (3) the care of airplane stock, (4) the composition and use of glues, (5) the manufacture and testing of ply wood, (6) wood in airplane construction, (7) moisture-resistant finishes, and (8) wood airplane parts.

REPORT No. 65.

THE KILN DRYING OF WOODS FOR AIRPLANES.

By Harry D. Tiemann.

I. INTRODUCTION.

KILN DRYING UNDER WAR CONDITIONS.

The exigencies of the war and the scarcity of air-dried material necessitated the kiln drying, immediately from the green condition, of practically all of the wood used in the United States for airplanes. This was a complete reversal of established practice and, from the standpoint of commonly accepted beliefs, was a dangerous innovation. England and France specified against "kiln drying" airplane woods, but in certain instances permitted "conditioning," that is, allowing the lumber to remain in a slightly heated dry room, usually at 25° C. (77° F.) or 30° C. (86° F.). A higher moisture content, however, was allowed there than in this country, the British requirement being 15 per cent for most woods and 18 per cent for ash, with an allowable variation of 3 per cent.

Perhaps the term "kiln drying" has an unfortunate association with lime or pottery or brick kilns, in which the material is baked. It must be admitted that the results formerly obtained in kiln drying lumber tended to create a prejudice in favor of the time-honored methods of slow air seasoning. The application of artificial heat, in the absence of thorough scientific knowledge of the principles involved and the development of a correct technique, resulted in much injury to the wood in checking, loss of strength, and warping.

Within the last 10 years the United States has taken the lead in placing the subject on a technical and scientific basis. It is now a well-established fact that many species of wood can be dried from the green state with better results than can be obtained by the irregular and unscientific method of air drying. While the chief reason for kiln drying in the past has been a saving of time, as the methods are perfected the superiority of the results obtained, from a quality standpoint, will be an increasingly important consideration.

Ordinary air seasoning, on account of its vicissitudes due to inability to control the process, is far from an ideal method of conditioning, even though the element of time did not enter into the question. This is particularly true for the more refractory and the more valuable woods and for all woods which are required for very exacting purposes, such as airplanes. It should not be overlooked, however, that a very gradual seasoning at air temperature, provided conditions are properly controlled, can not be excelled in its effect upon quality. This is true for the reason that the moisture difference between the outer surface and the interior is thereby kept at a minimum, so that no appreciable stresses are brought about by unequal shrinkages.

Because of the shortcomings of air seasoning various auxiliary methods have been sometimes used, such as preliminary soaking for years in ponds of water (still practiced in parts of Japan and Sweden) or burying in the ground or in manure.

Although the popular prejudice against kiln drying has not been entirely removed, especially in European countries, this method of conditioning lumber is now a scientific art and not a haphazard guess. Exhaustive strength tests made recently by the Forest Products Laboratory have shown beyond question that properly kiln-dried wood is just as strong, tough, and stiff as the best air-dried material.

Kiln drying for special purposes, such as airplanes, should be looked upon as a highly technical art. Lumber can be much more easily injured in a dry kiln than if left to dry in a shed exposed to the air, and unless the kiln drying is properly conducted air drying is safer. But if the kiln is in charge of a techincal expert, and the process is carried on in a scientific manner, kiln drying is greatly to be preferred to ordinary air drying.

The exigencies brought about by the war left no choice but to use kiln-dried material. To air dry Douglas fir wing beams requires ordinarily from 12 to 18 months. They may be kiln dried in 18 to 24 days. To air dry hardwood propeller stock takes at least one and preferably two years. The same material can be kiln dried and brought to equally good condition in a month's time. Air drying was, under the circumstances, wholly out of the question.

QUALITIES OF PROPERLY DRIED WOOD.

Whether kiln dried or air dried, the success of the seasoning process depends upon the extent to which the following requirements are met.

The material should be free from surface and end checks. Such checks are not necessarily visible. They may develop in the drying process and close up again when it is completed. This does not rectify the injury; the checks are still present, though pressed tightly together. Such material is unsuitable for airplanes.

The wood must be entirely free from internal checks, or "honeycombing" (see Pl. II). Such checks may be invisible upon the surface, but are evident when the stick is cut into.

The wood must be free from "casehardening." Casehardening is due to internal stresses. It is discussed in detail on page 19. Casehardened wood warps and cups when resawed or cut into small pieces (see Pl. III). Sometimes the internal stresses may be only temporary, due to unequal moisture distribution, and disappear when the moisture equalizes. In that case they are not serious, provided resawing does not take place in the meantime. Or they may remain in the wood indefinitely. Such stresses are of course detrimental.

The moisture must be uniformly distributed. In poorly dried lumber, portions of it may still retain some free water while other portions are very dry. Or there may be a wet core in the center while the outside is dry (see Plate IV, fig. 1.) Both conditions are extremely bad, as it will require an excessively long period before the moisture will equalize, and in the equalizing process the wood is subject to all the dangers which it faced in the original drying. Wood should never be manufactured into finished parts while the moisture distribution is unequal, since the relative dimensions are certain to change when the moisture finally equalizes, so the parts will no longer correspond in size.

The strength and toughness of the wood must be at a maximum. High temperatures and excessive internal stresses during drying cause injury to the strength and toughness. The effects vary considerably with different species. Softwoods as a rule are less subject to injury of this kind than are hardwoods. Excessive drying may of itself cause brittleness, even though the wood has subsequently reabsorbed moisture. For this reason the drying must not be carried too far. The requirements for airplanes are so exacting that material which would be entirely satisfactory for commercial uses might be altogether unsuitable for airplanes. Visual inspection of the dried wood is inadequate, since injury to strength may occur without any defect visible to the eye. Hence the drying process itself must be closely watched and controlled.

The wood should be free from excessive collapse and free from warping. Collapse is a sinking in of the fibers (see Plate IV, fig. 2) much in the same way that a rubber tube collapses when subjected to an internal vacuum. Certain species are peculiarly subject to this phenomenon.

In ordinary commercial work, drying without loosening the knots or causing them to protrude is a prime consideration. In conditioning airplane stock it is of course unnecessary to give consideration to this point, since all knots of any consequence are excluded.

Shrinkage should be the minimum consistent with securing the other qualities. It is not an independent factor; in fact, the very conditions most favorable for least shrinkage are also those most favorable to the development of internal stresses and casehardening. Shrinkage, if not unreasonable in amount, must therefore be largely disregarded.
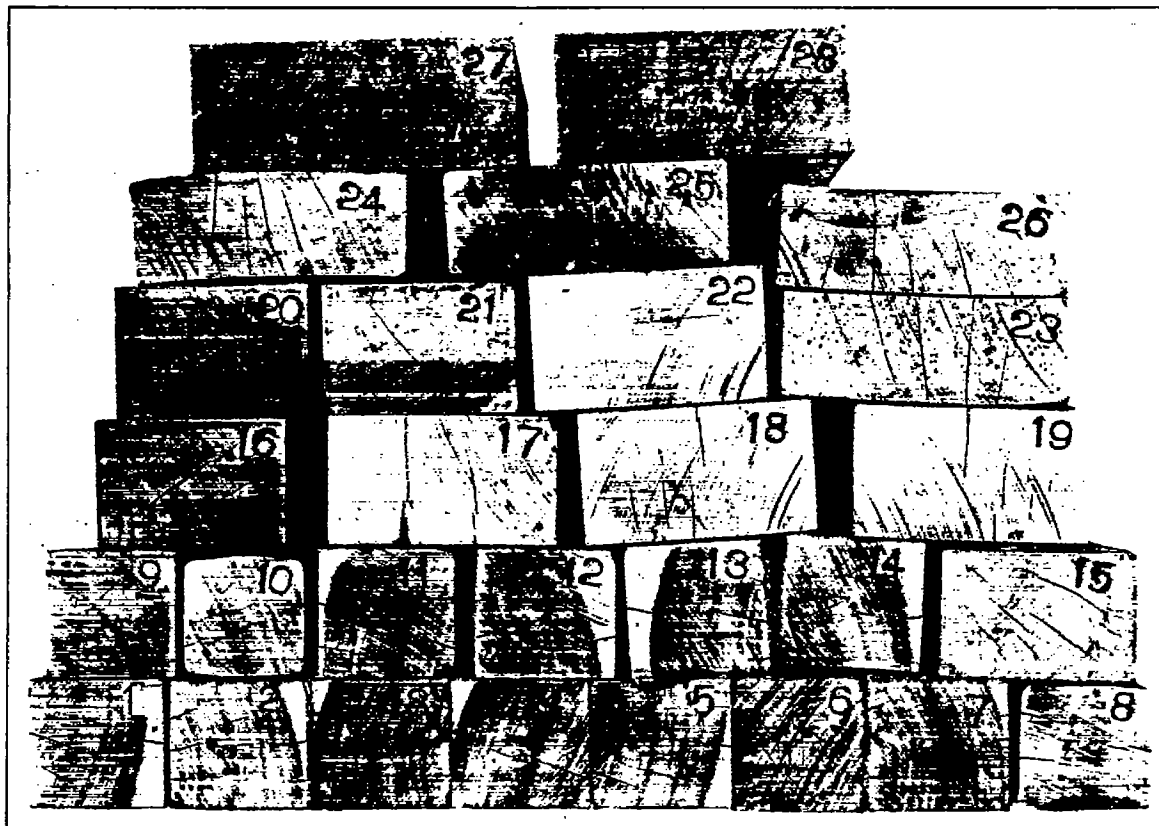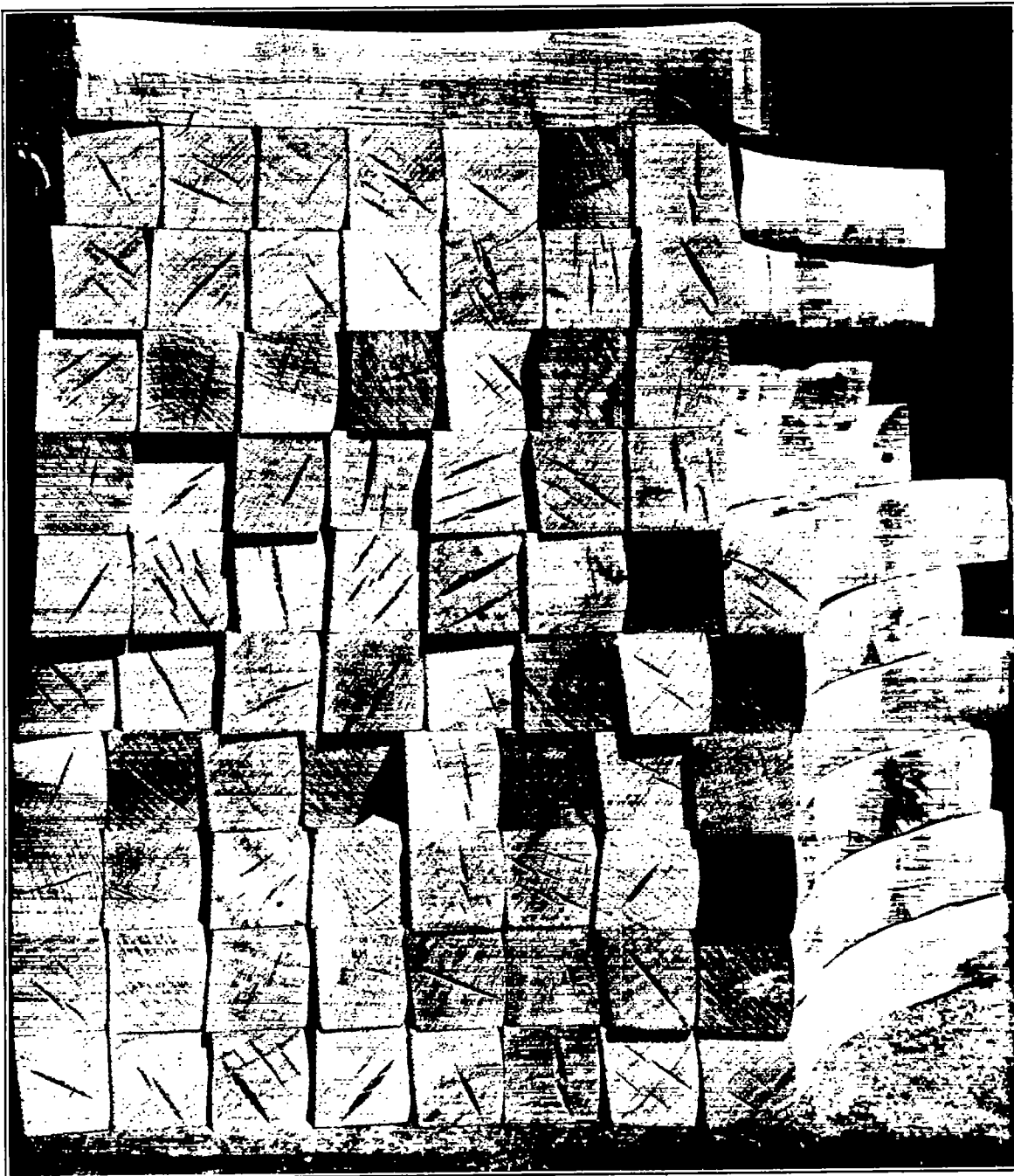
PLATE I.

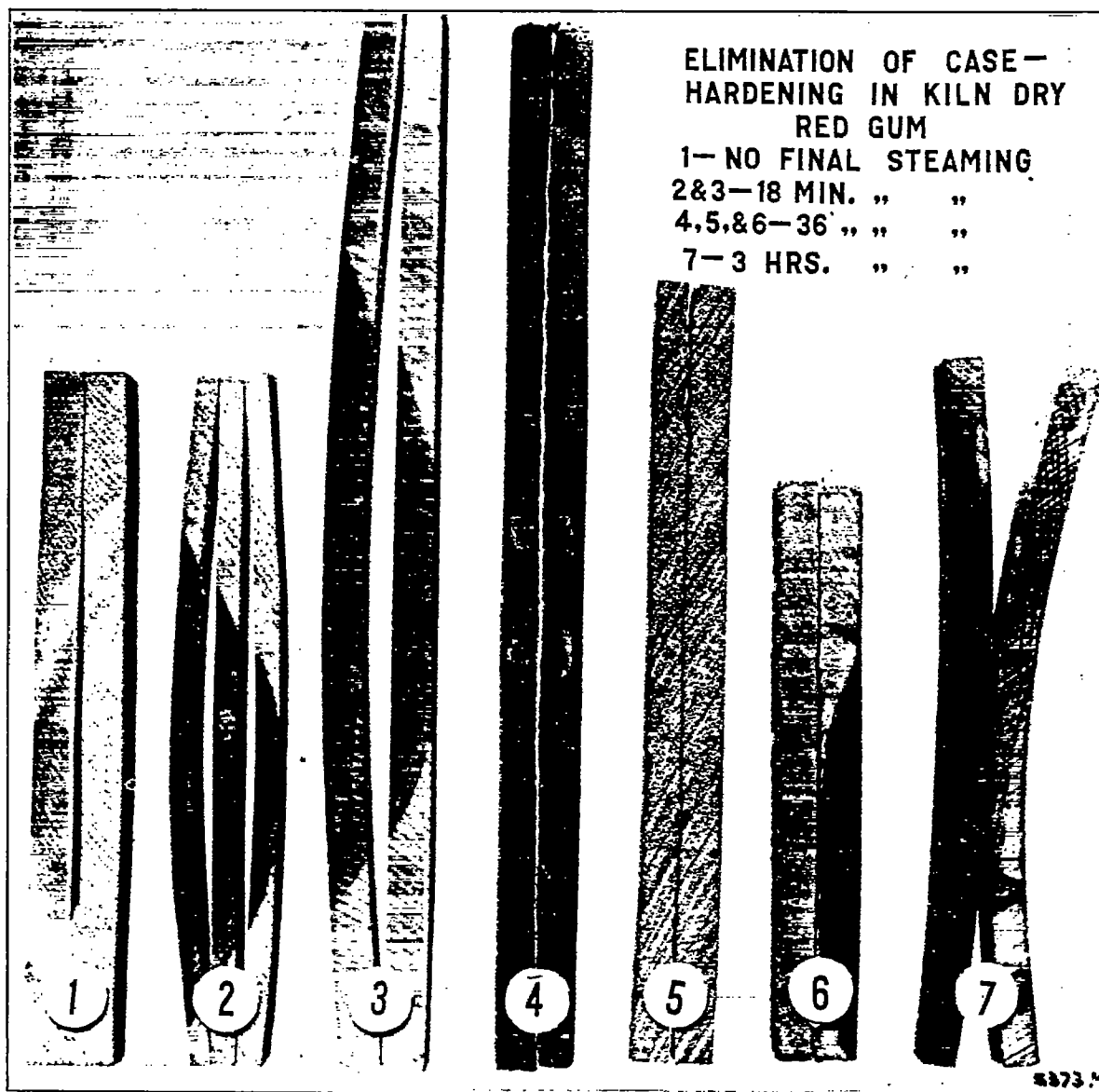FIG. 1.—STOCK WHICH HAS BECOME SURFACE CHECKED IN AIR DRYING.

FIG. 2.—THE SAME MATERIAL SHOWN IN FIGURE 1 AFTER KILN DRYING.

The checks have closed up, but the injury remains.

PLATE II.

BADLY HONEYCOMBED OAK STOCK.

Result of too severe casehardening in drying.

PLATE III.

ELIMINATION OF CASE—
HARDENING IN KILN DRY
RED GUM
1— NO FINAL STEAMING
2&3—18 MIN. „ „
4,5,&6—36 „ „ „
7— 3 HRS. „ „

CASEHARDENING EVIDENCED BY CUPPING OF THE BOARDS WHEN SAWED THROUGH PARALLEL TO THE SURFACE.

In Nos. 4, 5, 6 the stresses have been neutralized by steaming 36 minutes. In No. 7 the stresses were reversed by steaming 3 hours.

PLATE IV.

FIG. 1.—PARTIALLY DRIED WOOD WITH AN AREA OF FREE WATER REMAINING IN THE CENTER.
This block is in the first stages of casehardening. 3½ by 3½ inch oak wheel rim.
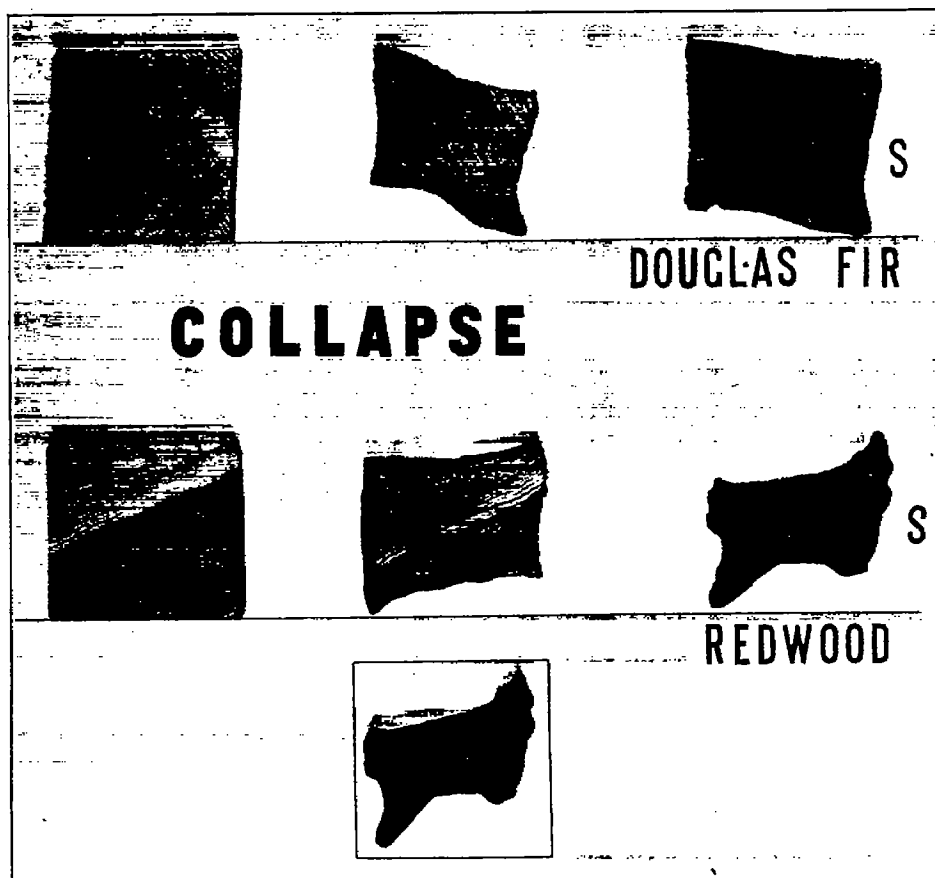

FIG. 2.—EXTREME CASE OF COLLAPSE IN 2 BY 2 INCH STICKS OF DOUGLAS FIR AND REDWOOD,
PRODUCED BY HIGH TEMPERATURE WHILE MOIST.

There is no positive means of determining whether a piece of wood has been kiln dried or air dried, if the drying has been properly done, except where the temperatures used have been sufficiently high to harden the resins or gums or to discolor the wood. However, the outer layer of kiln-dried wood only a few days out of the kiln is apt to be considerably drier than the inside, whereas air-dried wood will generally be of uniform moisture content because it has had plenty of time for the moisture to equalize, or it may be even drier in the center than on the surface. But after the kiln-dried wood has been allowed to stand for several weeks, its moisture may become evenly distributed.

EXACTING REQUIREMENTS OF AIRPLANE STOCK.

For ordinary commercial purposes a reduction in strength of 15 or 20 per cent below the standard is of little or no importance in comparison with honey-combing, checking, and case-hardening, which, in the order named, are the most serious injuries likely to occur. Collapse, warping, and loosening of knots are also of importance, but are not likely to give trouble in any treatment which does not produce the first-named injuries. As these conditions are all visible to the eye, it is comparatively easy to adjust the drying operation until they are eliminated. Moreover, in most cases a slight checking, particularly when these checks finally close up again, is not considered detrimental, and for some purposes quite severe casehardening is not especially objectionable. Unequal moisture distribution, however, is always bad, except for the very roughest kind of work. Collapse, while quite common, does not occur in sufficient quantity to cause trouble, and warping is usually avoidable by proper care in piling. Considerable lee-way is therefore possible in ordinary commerical drying operations, which explains the wide differences in the methods used. Even so, however, enormous losses exist which might well be wholly avoided by more care and intelligence in the treatment and in the design of the kilns. Moreover, the more exacting the requirements of the product, as for the best cabinet work, tools, musical instruments, etc., the greater refinement is necessary in the drying process.

For airplanes, however, strength and toughness are the prime requirements, and these qualities can not be determined by visual inspection. This fact renders the drying of lumber for airplanes a much more difficult and refined operation than for most other purposes. Actual mechanical tests are the only means of determining with any degree of certainity whether the material comes up to the standard. Since the dry kiln operator can not be guided by the appearance of the material, it is necessary to follow quite strictly certain prescribed specifications as to the drying operations. Different species require different treatments, as some are injured by conditions which are not harmful to others.

RELATION BETWEEN STRENGTH AND DRYNESS.

Dry wood is naturally very much stronger than wet. The crushing strength of green or wet spruce is increased *over fourfold* merely by drying [1]. It follows that the question what effect any particular process of drying has had upon the strength is necessarily a comparative one. From the mere fact that it has been dried, the wood has presumably been made stronger; the question is to what extent, or in other words whether the maximum of strength has been obtained. The answer to such a question can only be given through a comparison with some other drying process assumed as a standard. In making such a comparison the degree of dryness obtained must also be taken into account, since the strength increases progressively with reduction in the moisture content. For example, air-dried material may be taken as a standard. In that case the comparison would be made between kiln-dried material and air-dried wood of the same moisture content.

To make this matter clear and to facilitate further discussion of the general subject it is necessary to have in mind the basic facts regarding the composition of wood and the manner in which it dries.

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[1] Forest Service Bulletin 70, "The Effect of Moisture upon the Strength and Stiffness of Wood," by H. D. Tiemann, 1906. Forest Service Circular 108, "The Strength of Wood as Influenced by Moisture," by same author.

II. HOW WOOD DRIES.

THE COMPOSITION OF WOOD.

Wood is made up of minute cells, arranged somewhat as the cells in a honeycomb except that the cells in wood are very much longer in proportion to their width than in a honeycomb, and are not as uniform. In the "softwoods" (gymnosperms) the vertical cells are fairly uniform in shape and size; but in the "hardwoods" (angiosperms) they vary greatly, some being fifty times as wide as others, the wide ones being termed "vessels" or "pores," and the narrow ones "wood fibers." Interspersed between these vertical cells and fibers and lying in a horizontal radial direction are the medullary rays, appearing as the "silver grain" on quarter-sawed oak. The medullary rays are composed of short, blunt, thin-walled cells, similar to pith tissue, and are shaped like two-edged swords set edgewise.

Plate V is a cross section of a gymnosperm (*Picea rubens*), and Plate VI of an angiosperm (*Quercus rubra* or *borealis*), both magnified the same amount, 250 diameters.

The substance of which wood is composed is half as heavy again as water; its specific gravity is 1.56. It is organic and consequently very complex in structure. The cell walls are thought to be built up of small particles closely laid together, the interstices being capable of filling up with moisture. The foundation part of this substance is known as cellulose. With it is combined another material called lignin which adds to the strength of the cell walls and gives them a color.

MOISTURE AND ITS REMOVAL.

Wood in the living tree contains a great amount of moisture, varying from 30 per cent of the dry weight in the heartwood of some conifers, to over 200 per cent in some of the hardwoods. This moisture content must be greatly reduced before the wood is fit for use for most purposes.

In order to pass out from the interior of a board or timber the water must ordinarily pass transversely from cell to cell and evaporate from the surface. It is true that it can travel lengthwise very much more rapidly, as is evidenced by the end checking of lumber, but end drying can not be counted upon for removal of moisture from the center of a long stick. This process of transfusion from cell to cell is very slow, so that in ordinary air drying it takes 1-inch boards from six months to three years to reach 12 or 14 per cent moisture content, depending upon the kind of wood and the conditions under which it is dried.

In kiln drying, the process is greatly hastened by increasing the temperature and the air movement, thus increasing the rate of surface evaporation. This necessarily increases the differential in moisture content between the interior and the outer surface, since the rate of transfusion of moisture from the interior outward is partially proportional to this moisture difference. While the increased temperature presumably increases the transfusibility of the wood, it does not do so in proportion to the increased rate of surface evaporation. This necessary increase in the moisture difference brought about in order to hasten the drying is what causes the main difficulties in the kiln drying of woods.

These difficulties are due to the changes which take place in the wood itself in connection with the drying process after it has reached a certain point. Water exists in green wood in two forms—as liquid water contained in the cavities of the cells and pores and as "imbibed" or hygroscopic water intimately absorbed in the substance of which the wood is composed. The removal from the holes or pores of the free water will evidently have no effect upon the physical properties or shrinkage of the wood,[1] but as soon as any of the "imbibed" moisture is

[1] An exception to this statement occurs in certain species, notably in western red cedar (*Thuja plicata*), in eucalyptus, and in redwood (*Sequoia sempervirens*), in which a collapse of the cell walls takes place in spots or bands during the evaporation of the free water. This collapse occurs only in excessively wet regions and when the wood is dried at too high a temperature. The explanation of this peculiar phenomenon appears to be that the cell walls, which are practically impervious to air while wet, but through which water may readily pass, become soft and plastic when heated. Under this condition those cells which are completely full of water to start with are subjected to an internal suction or tension produced by the depletion of the water in the cavity by its evaporation through the cell walls. The cells then collapse like rubber tubes, one layer after another.

PLATE V.
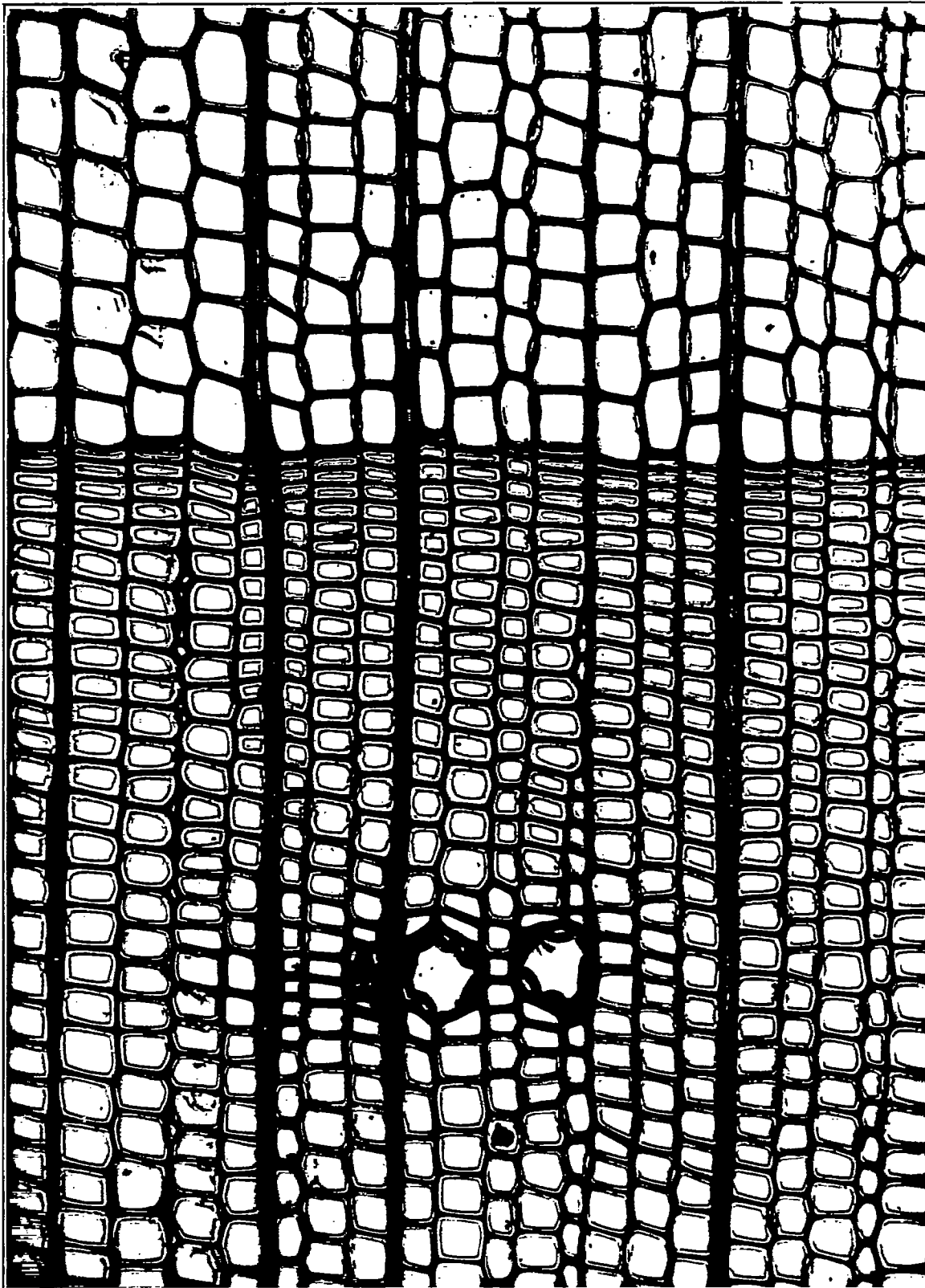
MICROSCOPIC SECTION OF A GYMNOSPERM ("SOFTWOOD"), A PIECE OF RED SPRUCE (PICEA RUBENS) AT JUNCTION OF TWO ANNUAL RINGS.

The vertical lines are the medullary rays (radial). The center of the tree is below. Two resin ducts are visible in the summer wood. Magnified 250 diameters.

PLATE VI.
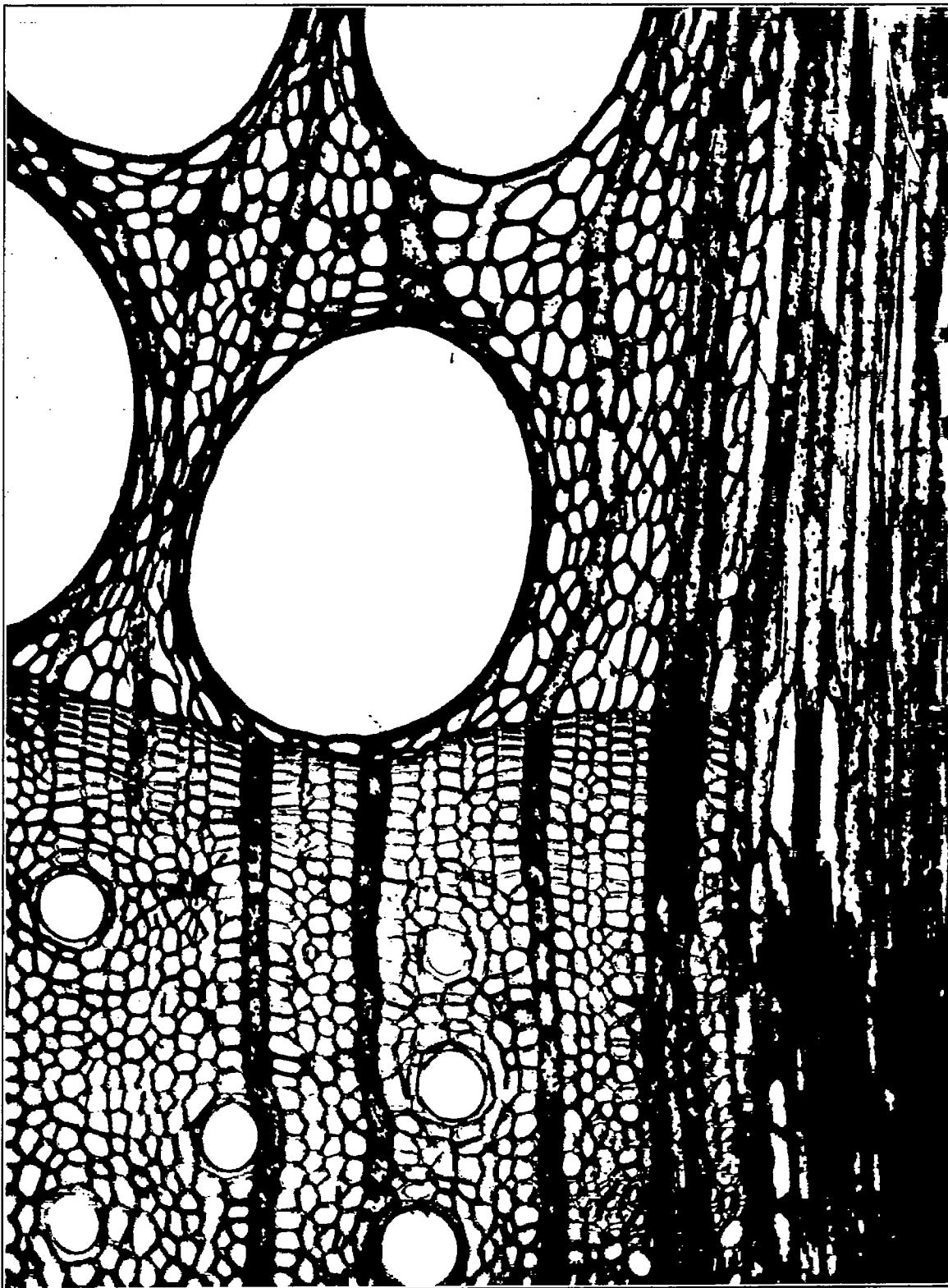
MICROSCOPIC SECTION OF AN ANGIOSPERM ("HARDWOOD"), A PIECE OF RED OAK (QUERCUS RUBRA OR BOREALIS) AT JUNCTION OF TWO ANNUAL RINGS.

The open vessels or "pores" are shown in the summer wood and a large medullary ray (radial) on the right. The center of the tree is below. Magnified 250 diameters.

removed from the cell walls shrinkage begins to take place and other changes occur. The strength also begins to increase at this time. The point where the cell walls or wood substance becomes saturated is called the "*fiber-saturation point*," and is a significant point in the drying of wood. In some cases the free water can easily be removed by heating it above its boiling point, but in many cases this will injure the wood and in others the water contained in the cells themselves will not be forced out in this manner, only that from the open vessels or pores passing off in vapor. The chief difficulties, however, come in evaporating the free water where it has to be removed through its gradual transfusion through the cell walls instead of by boiling. The problem lies in the danger of drying the surface below its fiber-saturation point while free water still remains in the interior.

The fiber-saturation point lies between a moisture condition of 20 per cent and one of 35 per cent of the dry weight of the wood, depending upon the species.[1] In the living tree the wood is always above its fiber-saturation point.

PROPERTIES AND BEHAVIOR OF WOOD IN CONNECTION WITH MOISTURE REMOVAL.

GENERAL.

Different species vary greatly in the phenomena of drying. This is due to the fact that the properties which all possess in varying degree are combined in very different proportions. In consequence the response to a given set of conditions is of a widely diverse character.

One of these properties is the capacity to transfuse moisture. The rate of transfusion is very slow in some woods, as oak, and fairly rapid in others, as pine. The relation between rate of transfusion and temperature has already been mentioned in the preceding section. Transfusibility is, of course, the fundamental property of wood which makes drying possible, and the art of drying consists in so controlling transfusion, through control of the factors of temperature, humidity, and circulation on which its rate depends, that the changes in the other properties of wood which accompany drying are as favorable as possible.

Hygroscopicity is a property of wood closely related to transfusibility. It is the property by virtue of which wood substance absorbs or loses moisture in proportion to the relative humidity of the air, the rate varying slightly according to the temperature.

Change in color occurs in some species in drying. This is distinct from sap stain or colors caused by fungus or bacteria. It is notable in hard maple sapwood and in sugar pine. In the maple a moist, warm atmosphere is conducive to this coloration.

Under moist conditions combined with high temperature the wood substance becomes soft and plastic, while, on the other hand, as the moisture falls below the fiber-saturation point the wood substance hardens and stiffens. The effect of temperature upon plasticity varies greatly with different species, some, as, for example, western red cedar, redwood, oak, and eucalyptus, becoming excessively soft, even at temperatures as low as 150° or 170° F.

Tenacity, or cohesion between the fibers, easily breaks down with increase in temperature in such woods as western larch and the southern swamp oaks, thus permitting internal stresses to cause checking with great readiness.

Brittleness is produced by excessive drying.

Strength in wood is, of course, a very complex matter. It can not be discussed at length here. It is not a single property, nor even strictly speaking a group of properties, but is of various kinds, each kind being the result of more fundamental properties of the wood substance and of its condition with respect to such matters as internal stresses, checks, and other defects. The subject of the strength of woods for airplane stock is covered by another contribution to this series of monographs, entitled "Effect of Kiln Drying on the Strength of Airplane Woods." Among the phenomena which attend the drying of wood are two of such fundamental importance as to require further consideration. They are not independent, for the second is largely an effect of the first, but must be discussed independently. Both affect the strength as well as the form of the wood. They are shrinkage and casehardening.

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[1] See Forest Service Circular 108, "The Strength of Wood as Influenced by Moisture."

SHRINKAGE.

On page 15 it was stated that shrinkage does not take place until removal of the "imbibed" water from the cell walls begins. To this statement certain species of eucalyptus, oak, and probably other woods appear to present an exception in that shrinkage begins at a moisture condition of from 80 to 90 per cent of the dry weight. It is probable that this apparent shrinkage may in reality be a form of collapse.

Wood shrinks differently in different directions—as a rule it may be considered to shrink twice as much circumferentially as it does radially, and about one-fiftieth as much longitudinally, although this also varies in different species. Shrinkage continues until the substance is perfectly dry ("oven dry"), and it begins to swell again by absorption of moisture as soon as it is exposed to moist air. Alternate shrinking and swelling is inevitable with changes in the relative humidity of the surrounding air. This causes the so-called "working" of the wood. Different species vary greatly in this respect.

Wood shrinks more when dried slowly under moist conditions, especially at high temperature, than when dried rapidly.[1]

CASEHARDENING.

Casehardening is a somewhat ambiguous term as commonly used. It signifies in general a hardened case on the outside of the wood. In metal tempering the same word denotes the condition produced when the outer surface of an iron casting is changed to steel by heat treatment which removes part of its carbon. Doubtless the apparent analogy led to application of the word to conditions developed by heat treatment of wood. The analogy, however, is not a very good one and should not be followed too closely.

In seasoning wood a condition often arises in which the outer portion has become dry and hard, while the inner portion remains wet and loses moisture so slowly that drying seems almost at a standstill. This condition is due to the fact that the outer portion dried out faster than transfusion from the interior could take place, with the eventual result that the wood substance has become hardened and has largely lost its capacity to transfuse moisture. Because of the hygroscopicity of wood, however, the outer portion may in time, under favorable conditions, take up moisture again until a condition favorable to transfusion is again established, and drying may proceed at the normal rate. By steaming casehardened wood in this condition the fibers can be very quickly softened so that the normal seasoning process can be resumed.

But casehardening involves other factors. As the wood dries it also shrinks. If the outer and inner portions of a stick of wood dry unequally, there arises presently a condition in which unequal stresses have been set up. Such stresses are manifested by a tendency to deformation if the wood is cut in the manner presently to be described. From the standpoint of successful conditioning of wood in a dry kiln the most important aspect of casehardening is that which has to do with the unequal stresses which are brought about through unequal rates of shrinkage between the outer and inner portions as moisture is removed.

These stresses begin to be exerted as soon as a portion of the wood dries below its fiber saturation point. Since it is impossible, practically speaking, to season the wood rapidly without bringing about a condition in which unequal shrinkage takes place, a certain measure of casehardening may be said to be inevitable in kiln drying. Such stresses do not occur, however, to any appreciable amount when wood is very gradually seasoned, as in air drying under damp conditions.

But to understand fully the phenomena of casehardening account must be taken of still another factor. As soon as the moisture content of wood passes the fiber saturation point it begins not only to shrink but also to harden. The result is to set up a condition in which the wood has partially lost its capacity to shrink. It has become more rigid. This may or may not result in establishing what may be called a permanent differential of shrinkages between the outer and inner portions of the wood—that is, a condition in which one portion is always prevented

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[1] Probably this is a secondary result dependent upon the factors of casehardening and collapse.

PLATE VII.
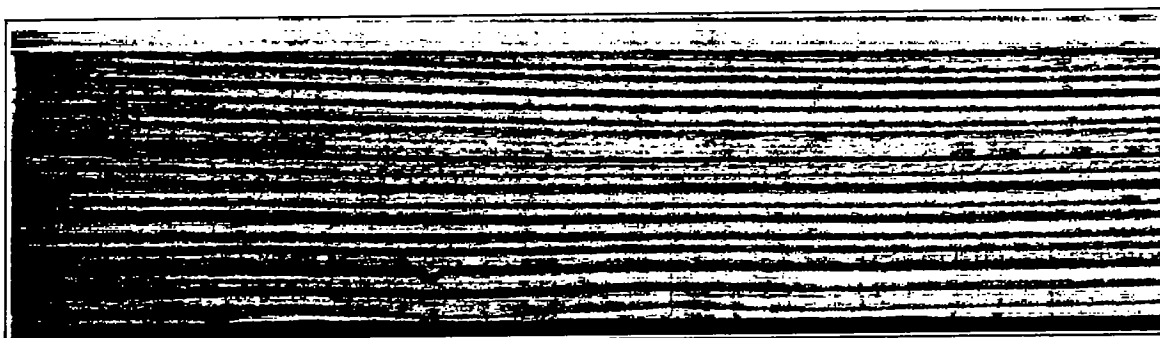
"WASHBOARDING" IN AN INCH BOARD OF BLUE GUM (EUCALYPTUS GLOBULUS) DUE TO THE ALTERNATIVE
COLLAPSE OF THE ANNUAL RINGS.

This board was perfectly flat when placed In the kiln, as is evidenced by the band-saw marks running across the surface.

by another portion from shrinking as much as it would if free from a counteracting force.   If such a permanent differential is not established, the casehardening will be temporary; if it is established, the casehardening will be permanent.

Four variable factors, then, are present in casehardening, and affect the result, namely, moisture content of the wood, degree of shrinkage, internal stress, and the period at which the fibers become hardened or set.   These factors are partly dependent one upon the other.   Temperature is still another factor, but may be treated as an independent variable.

OTHER EFFECTS OF DRYING.

Warping results from unequal shrinkage or from a warped direction of the fibers.   Cupping is due to unequal shrinkage of slab cut boards radially and circumferentially and is simply explained by geometrical relations.

Washboarding is due to unequal shrinkage of adjacent layers of the annual rings of wood, and appears on radially sawed (quarter sawed) lumber.   (See Pl. VII.)

Collapse of the cells may occur in some species while the wood is hot and moist.   This collapse is distinct from the shrinkage which takes place in the wood substance and is due to a different cause.

Checking and honeycombing are caused by unequal shrinkage, crooked grain, and casehardening.

III. THE ART OF CORRECT KILN DRYING.

Were it not for the unequal shrinkage and the slow rate of transfusion of the moisture from cell to cell, the drying of lumber would present no more difficulty than the drying of wet cloth or clay. The problem of kiln drying wood would be merely one of conducting the requisite amount of heat to the material to supply that required for vaporization, which at 163° F. is 1,000 British thermal units of latent heat per pound of water, plus a small additional amount (about 30 B. t. u. per pound of dry wood)[1] required to overcome the attraction of the hygroscopic material for the moisture. By use of a temperature higher than the boiling point corresponding to the given pressure, the moisture would pass off directly in proportion to the quantity of heat supplied. But the process is more complex in the case of wood.

EFFECT OF THE SURROUNDING CONDITIONS ON DRYING.

There are just three conditions which it is essential to control properly for correct drying: (1) Circulation of the air, (2) humidity, and (3) temperature; and it is important that these conditions be uniform throughout the kiln.

EFFECT OF CIRCULATION.

Unless the circulation is sufficient to convey throughout the pile of lumber the heat necessary for evaporating the moisture, and also sufficient to carry away the vapor, uniform drying is impossible. The humidity of the air throughout the pile is dependent upon the circulation For drying an isolated single stick of lumber circulation is unimportant, since the stick would receive heat on all sides by convection or radiation and the moist vapor would pass away by diffusion; but for a pile of lumber of any considerable size, a decided movement of the air through the pile is necessary.

Since evaporation involves a consumption of heat and its transformation into latent heat, and at the same time an increase in the humidity of the air immediately surrounding the object, it is evident that drying in all parts of a pile of lumber can not take place under the same temperature and humidity condition at one and the same time. Where the air passes through a pile in a definite direction the temperature is highest and humidity the least at the place where the air enters the pile, and the temperature is lowest and the air dampest where it leaves the pile. Consequently drying takes place progressively through the pile in the direction of the air circulation. The more rapid the circulation the more uniform will be the conditions through the pile. Something of this same condition exists whether the circulation is in a definite direction or is irregular, only irregular circulation does not lend itself to analysis and variations are more irregular and usually much greater in amount. Variations of from 30° to 50° F. are not uncommon when circulation is indefinite, and humidity variations are from very dry to saturation.

EFFECT OF HUMIDITY.

If it were merely a question of evaporating moisture the most economical drying system would be one in which the air entered the pile of lumber in the driest attainable cond tion and left the pile in a saturated condition.[2] But the more important part played by the humidity is its physical effect upon the wood. There is a natural balance between the hygroscopic moisture assumed by wood and the relative humidity of the surrounding air at a given temperature.[3] For the avoidance of checking and casehardening it is essential that the surface of the piece of wood be kept comparatively moist while the water is passing from the center to the surface. In other words, the surface must not dry at a more rapid rate than the moisture transfuses

[1] Unpublished report, Forest Products Laboratory, by Frederick Dunlap.
[2] See Department of Agriculture (Forest Service) Bulletin 509, "The Theory of Drying," etc., by H. D. Tiemann, pp. 22 and 23.
[3] "The Kiln Drying of Lumber," by H. D. Tiemann, pp. 103 to 105 and 263.

from the center of the stick to the surface.   This is brought about by retaining a definite amount of humidity in the air during the drying operation.   This fact is of special significance in the drying of green lumber, where the aim is to keep the surface *as near its fiber saturation point as possible until all the free water has evaporated from the center* after which the moisture condition of the surface can be gradually reduced by lowering the humidity.   Humidity is also of importance in establishing the final moisture content before removal from the kiln.   As there is a definite relation between relative humidity and the percentage of moisture which the wood will retain, it is evident that by regulating the final humidity in the kiln, overdrying may be prevented.

EFFECT OF TEMPERATURE.

The temperature influences both the mechanical efficiency of the operation and the physical effect upon the wood.   In general, the higher the temperature the more efficient is the operation; but this is completely and definitely limited by the effect upon the wood.   The temperature at which drying may be safely conducted without injury to the material varies greatly with different species.   For example, oak must be dried to start with at not over 110° F., while Douglas fir for commercial purposes (not for airplanes) will stand over 225° F. without appreciable injury.

The effect of high temperature is (1) to soften the fibres; (2) to reduce their cohesion in tension, so that slight stresses will cause separations or checking and honey-combing; (3) to affect permanently the strength if certain limits are exceeded; (4) to tend to increase the shrinkage and produce collapse; and (5) presumably to increase the rate of transfusion of the moisture through the wood.   Chemical changes also occur and the hygroscopicity of the wood is reduced.

These different effects are produced proportionally very differently in different species, so that the resultant effect of a given temerature with one species may be altogether unlike that with another.   Thus, high temperature greatly softens the fiber of oak but it reduces its cohesion in a greater proportion, so that checking is more liable to occur at high than at low temperatures.   On the other hand, in most softwoods the cohesion is not reduced relatively to so great an extent, consequently they may be dried at higher temperatures, normally than oak and similar hardwoods.

On account of the softening of the fibers and the increased transfusion, casehardening is less at a high than at a low temperature if the drying rate is the same in both cases.

IV. DISCUSSION OF DRY KILNS AND MEANS OF CONTROLLING THE ESSENTIAL CONDITIONS.

A dry kiln is sometimes thought of as a hot box or baking oven, or as a certain shaped building; rightly, however, it should be considered as an apparatus for conditioning lumber by supplying certain definite requirements. The essential requirements are adequate and uniform circulation throughout the pile of lumber; control of humidity at all time; control of temperature; and ability to steam the lumber quickly and effectively whenever necessary for removal of casehardening and killing of mold. These essentials have already been discussed.

SYSTEMS OF KILN OPERATION.

There are two distinct ways of handling lumber in kilns. One way is to place the load in a chamber where it remains stationary throughout the operation, while the conditions of the drying medium are varied as drying progresses. This is the "compartment" or "charge" system of handling the lumber.

The other way is to run the lumber on a wheeled truck into one end of a long chamber and gradually shove it along toward the other end, where it is taken out when the drying is completed. An attempt is made to keep the end of the kiln where the lumber enters moist, and the other end dry. This is known as the "progressive" system of operation, and is one commonly used in large operations. It is the less satisfactory of the two, however, where careful drying is required, since the conditions can not be so well regulated and are apt to change with every change of wind and with every new load of lumber introduced. It is not to be recommended for use with airplane stock.

The compartment system can be arranged so that it will require no more kiln space or handling of the lumber than the progressive system; it does, however, require more intelligent operation, since the conditions in the kiln must be continually altered according to the progress of the drying. Either of these two systems may be used with almost any kind of dry kiln.

As a rule the progressive system employs a simple ventilated kiln such that the air enters at the dry end (where the lumber is taken out) through ducts placed in the bottom beneath the heating pipes, is heated as it rises between the pipes, thence passes through the lumber in a horizontal direction, opposite to that in which the lumber is being moved, and is finally discharged through chimneys at the damp end. The heating pipes usually extend only about two-thirds the length of the kiln from the dry end. Such kilns vary in length from about 60 to 150 feet and in width from 18 to 24 feet, and are about 14 to 16 feet in height.

METHODS OF SECURING CIRCULATION.

Pressure and superheated steam treatments are not suitable for airplane material; and the vacuum treatment, though suitable, is hardly practicable. It will, therefore, suffice to consider only atmospheric pressure treatments.

In general the circulation is produced in three ways:

(1) By external draught or ventilation, where the air is taken in from the outside, conditioned, passed through the kiln, and allowed to escape to the outside again.

(2) By recirculating the air within the kiln itself and removing the excess moisture by condensation.

(3) By forcing external air through the lumber by means of a fan or blower.

Combinations of these methods may also be used.

So long as the fundamental requirements already specified are definitely secured, any one of these systems may be used for drying airplane lumber, but they are not all equally satisfactory. The mechanical features having to do with the operation of the kiln, the accuracy and certainty of control of the conditions, and the amount and uniformity of the circulation differ greatly in their effectiveness in different types.

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VENTILATED KILNS.

In a purely ventilated kiln the circulation of air is usually either entirely too sluggish for drying green wood if the humidity is uniformly distributed, or if the draft is sufficient for drying the green wood the changes in the humidity are excessive. Usually the deficiency of the humidity in the air as it enters the lumber has to be made up by injecting live steam into the current of incoming air. This arrangement is often precarious. Changes in temperature of the outside air greatly affect the internal conditions. In general, ventilated kilns are not suitable for drying green airplane woods. They are much more suitable for drying air-dried lumber than green. It is difficult to maintain control of conditions in this type of kiln. Nevertheless, for certain kinds of drying such as 1-inch lumber of easily dried species a ventilated progressive kiln is probably the simplest, most easily operated, and most economical design possible.

RECIRCULATION KILNS.

In the ordinary type of recirculation kiln, pipe condensers are commonly used to remove the excess moisture from the air. Unless there is some additional means of increasing the circulation of the air, however, its natural movement is apt to be too slow for the rapid drying of green lumber except at high temperatures and low humidities, which are prohibitive for airplane stock. In the Forest Service humidity-regulated water-spray kiln,[1] which belongs to the internal-circulation class, the circulation is greatly accelerated by means of sprays of water uniformly spaced the entire length of the kiln and placed in narrow chambers, one on either side, or in a single chamber through the middle. The water sprays at the same time control the humidity of the air. This kiln has been largely used for drying airplane stock. Another means of producing the needed circulation is by placing fans directly in the kiln itself, and thus forcing the air through the lumber. The main difficulty of this plan is so to arrange the fans that a uniform circulation is produced in all parts. Humidity control is also somewhat difficult of accomplishment, as it depends upon leakages through the walls, canvas curtains or ventilators, together with the injection of live steam through perforated steam pipes. This type of kiln has been very successfully used in drying green airplane stock.

BLOWER KILNS.

In the third class a blower or fan is used to force in new air. This is usually placed outside of the kiln proper, and air is sucked out and returned to the drying chamber through ducts. Ventilation is secured by admitting more or less fresh air and allowing some of the return air to escape. Accurate control of conditions is usually difficult to maintain, since the slightest change in adjustments of the steam jets or of the dampers very quickly and progressively alters the conditions in the kiln. Such an arrangement is in what might be considered unstable equilibrium. Where a battery of kilns is used, a separate blower is required for each kiln, otherwise they can not be operated as independent units.

CIRCULATION CONTROL.

In the design of any kiln and method of piling it should always be borne in mind that the load of lumber itself, particularly when first introduced, acts as a powerful condenser. The evaporation is of itself a cooling operation, and calculation shows that the effect of evaporation is to increase the density of the humid air in spite of the fact that more vapor has been thereby added.[2] This means that there is a natural tendency of the air to descend as it passes through the lumber, particularly when rapid drying is taking place. The arrangement of the pile of lumber and the kiln, therefore, should be such as *not to oppose* but *to assist the natural gravity tendency.* Success or failure sometimes hinge on this point. Extensive observations under all kinds of conditions and in all kinds of kilns have shown that this theory of the downward tendency of the air through the pile is the correct principle.

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[1] See Appendix III.   [2] See Bulletin 509, "The Theory of Kiln Drying," etc., p. 27.

HUMIDITY CONTROL AND STABLE EQUILIBRIUM.

Humidity control is brought about in various ways, and its accomplishment is the most difficult problem in regulating the dry-kiln operation. In ventilated kilns the humidity is usually varied by the amount the dampers are opened, the moisture added to the air being that evaporated from the lumber. Very often steam jets are used where it is necessary to add humidity to the air; or vessels of heated water are used. In condenser kilns the temperature of the pipe condenser is altered, to change the humidity, by altering the flow of water through the pipes. Steam jets are also used to add humidity as required. In the blower kilns similar means are employed and, in addition, the dampers admitting fresh air are adjusted. In the Forest Service water-spray kiln the humidity is automatically controlled by regulating the temperature of the spray water. Hot water in the sprays gives a high humidity, while cold water acts as a condenser and gives a low humidity. The control is very direct and the water acts in addition as a stabilizer, preventing any sudden changes of conditions. The kiln is in a condition of what might be termed stable equilibrium.

TEMPERATURE CONTROL.

This is the simplest problem with which the dry-kiln engineer has to deal in the design of a dry kiln. When conditions are fairly uniform, the temperature may be approximately regulated by turning on a greater or less number of steam pipes, if the piping system is installed in independent units. Wherever high-pressure steam is available, temperature may be largely controlled by means of a pressure-reducing valve. Both systems combined increase the range obtainable. Very steady temperatures may be thus maintained, but the difficulty is that when the temperature begins to change it may continue to rise or fall progressively, and if not closely watched will soon pass the desired limits. Throttling steam valves by hand is not recommended.

The safest method is to use one of the many good makes of thermostat, having a control bulb which may be placed anywhere desired in the kiln, and connected to the operating mechanism by a long, flexible tube. Any degree of accuracy of temperature control desired can be secured by the use of a suitable instrument of this kind. Some are made to act directly upon the steam valve by the expansion of vapor contained in the bulb, or by the expansion of a liquid. Others are made to operate through an auxiliary or relay system, the motive power of which consists of air pressure or water pressure, which in turn operates a motor valve on the steam line.

For the most delicate control the air-pressure relay system has proved the best, while for certainty action and simplicity one of the direct-acting systems is to be recommended. Any one of these systems is satisfactory, and no kiln for accurate drying should be operated without some form of thermostat.

Heating systems as a rule consist of a series of ordinary iron pipes placed near the floor of the kiln. In blower kilns the air is often heated either by pipes or by furnace before it is forced into the kiln. Sometimes ordinary radiators are used. Whatever the heater, the main thing is to have it properly controlled and the heat uniformly distributed and constantly supplied.

A return bend system of piping has proved the most satisfactory for compartment kilns, as it gives uniform heating at both ends of the steam coil. The header system, while more commonly used, is apt to heat one end more than the other. This is particularly so when low-pressure steam is used and in high-pressure systems when a thermostat is placed on the feed line. If the traps fail to operate properly or the pipes become air bound, the drainage end is certain to be colder than the supply end. The return bend system, made up of several separately controlled coils of pipes, is strongly recommended. One-inch piping is very commonly used for dry kilns and often 1¼-inch and occasionally 1½-inch piping. For low-pressure steam the larger pipe is preferable.

Temperature control is especially important in drying airplane stock, since if certain limits are exceeded the strength and toughness are affected.

V. DETERMINATION OF CONDITIONS IN KILNS.

IMPORTANCE OF ACCURATE KNOWLEDGE OF CONDITIONS FOR AIRPLANE STOCK.

For airplanes, strength and toughness are the prime requirements, and these qualities can not be determined by visual inspection. Actual mechanical tests are the only means of determining with any degree of certainty whether the material comes up to the standard. These tests in order to be determinative must be made upon matched material from the same sticks, and the testing of the material and analysis of results is extremely complicated and difficult. How these tests have been made for a number of species at the Forest Products Laboratory, and the results secured, are set forth at length in another contribution to this series.

The fact that strength conditions can not be satisfactorily determined by visual inspection alone when airplane material is concerned renders the drying of such material a much more difficult and refined operation than that of drying lumber for most other purposes, and necessitates that the operator follow strictly certain prescribed specifications.

USE OF THERMOMETERS AND HYGROMETERS.

A single thermometer reading should never be relied upon, and it may be necessary to place thermometers in a dozen or more different places in the kiln and take readings of them all frequently throughout the entire run until the proper place for taking the controlling conditions has been determined upon. All thermometers should be checked together occasionally by placing their bulbs together and surrounding the set of bulbs with some insulating material, such as a dry woolen cloth. The kiln should be controlled not by an average of the various readings, but according to the conditions at some point or points carefully selected, after a study of all the readings. The success of the run may depend largely upon the judgment used in choosing the proper places for measuring the conditions. If the readings at the different positions in the kiln appear to be inconsistent, sets of readings should be taken at short intervals, both at a time when the temperature is rising and again when it is falling, and the thermometers moved about until consistent readings are obtainable. It is not always easy to predict where the hottest portion of the kiln will be, and even when this is found it may not necessarily correspond to the air temperature entering the pile of lumber. Furthermore, the air may enter the lumber at one place during the beginning of the run and at another place at the finish, in which case the place for measuring conditions controlling the run must be shifted accordingly. Or there may be no apparent place which might be considered as "entering air". In this case the hottest portion of the pile should be chosen as supplying the condition for controlling the run.

Since it is assumed that material from any portion of the pile is likely to be used in manufacture, it is necessary that no portion of the pile be subjected to conditions more severe than those specified. Hence it is necessary to govern the entire kiln by the most severe conditions to which any portion of the pile may be subjected, irrespective of whether other portions are drying too slowly or not.

In dry kilns where the circulation of the air is in a known direction, the proper place at which to measure temperatures and humidities for controlling the drying run is where the air first enters the pile of lumber. In the water-spray kiln this place is in the warm air flue (opposite the spray chamber side of the pile), about half way up the pile and about the middle of the flue. Ordinarily a thermometer or hygrometer so placed will not need to be shielded from radiation.

RECORDING THERMOMETERS.

While not essential, recording thermometers are very useful not only in furnishing a permanent record of the run but also in indicating how to control the conditions. While optical readings of glass thermometers give only points in the curve of operation, the recorder gives a continuous record; and it is very easy to learn from the recorder whether conditions are steady, variable, rising, or falling.

Unfortunately, recording thermometers have not proved altogether reliable and they should not be wholly depended upon. Standard glass thermometers should always be used in the kiln in addition to the recorders. The recorders should also be checked frequently with a standard glass thermometer.

The recorders most useful in dry-kiln work are those in which the measuring bulb is connected with the recording instrument by a long, flexible capillary tube filled with a fluid. The bulb is placed at the point where the temperature is to be measured, and the recording instrument in a convenient room, which should be at a lower temperature than the bulb.

These instruments are of four types, according to whether the fluid in the bulb and tube is (1), mercury, (2) some nonvolatile liquid, (3) gas, or (4) a volatile liquid which produces the pressure on the operating spring through vaporization of a portion of the liquid.

In the first three types it is important that the spring in the recording case and that portion of the tube not subjected to the temperature to be measured be kept at a fairly uniform temperature, since any changes in the temperature of any portion of the fluid contents will affect its pressure according to the relative volume affected. Compensating devices are usually attached to such instruments supposed to correct for such changes, but experience shows that they do not always compensate with complete satisfaction, especially in the case of the liquid-filled instruments.

The only instrument which is not subject to changes in temperature of any part of the vessel is one filled with a volatile liquid and its vapor. Since the action of this instrument is produced solely by the pressure of saturated vapor and not by the expansion of the liquid or gas, it is not affected by temperatures which are lower than the temperature of the bulb. Its action is the same as that of a steam pressure gauge; in fact, the thermometer is in reality nothing more than a saturate vapor pressure gauge; and since the pressure of saturate vapor is always the same at a given temperature, independent of the volume or of the lower temperature of the liquid, this form of thermometer is the most accurate and reliable if properly used. The main precaution is that no portion of the tube or the spring must be heated above the temperature of the bulb. The tube and spring will then be full of the liquid, and the vapor will be generated in the bulb in the presence of some of the liquid, which is always sufficient to fill part of the bulb as well as the tube and spring.

This form of instrument may be at once distinguished from the other three forms by the divisions on the dial, which in the others are uniformly spaced but in the vapor instrument widen out as the temperature increases. In one make a patented device is attached which comes into action at a prescribed temperature and narrows down the spacings.

In the gas-filled instrument it matters not at what height the recording dial is placed relative to the bulb; but in the liquid and vapor instruments the vertical height of the liquid column exerts a pressure, which requires a readjustment of the hands when this height is altered.

PLACEMENT OF RECORDING THERMOMETERS.

For the water-spray kiln the vapor form of instrument is recommended. Two separate bulbs operating on one dial are desirable, one to record the dew point, the other to record the entering air temperature. The dew-point bulb should be placed in the lower opening of one of the baffle boxes, on the spray-chamber side, but in such a manner that it does not receive the direct spray of water nor rest directly on the floor; and the tubing should extend through the spray chamber itself to the end of the kiln and pass directly out through the end wall. This is to insure that no portion of it becomes heated above the bulb temperature. The case also must be situated in a room which is cooler than the dew-point temperature to be measured. Care should be taken to see that the bulb is placed in a "live" part of the spray chamber and not where the conditions of spray or circulation are abnormal from any cause.

The bulb for measuring the temperature of the air entering the lumber (dry bulb) should be suspended in the warm air flue about half way to the top of the pile and midway across the flue, and the tubing should be carried horizontally on a level with the bulb through the flue to the end of the kiln and thence through the wall to the instrument. It must not pass near any hot pipes. So placed, the bulb need not be shielded from radiation. It is important that this bulb does not lie on line with the space between the ends of two piles, but it should come somewhere near in line with the middle of the pile. The same applies also to the dew-point bulb, since the circulation will be apt to be abnormal between the piles, and the true conditions of the air which enters and leaves the pile would not be correctly registered.
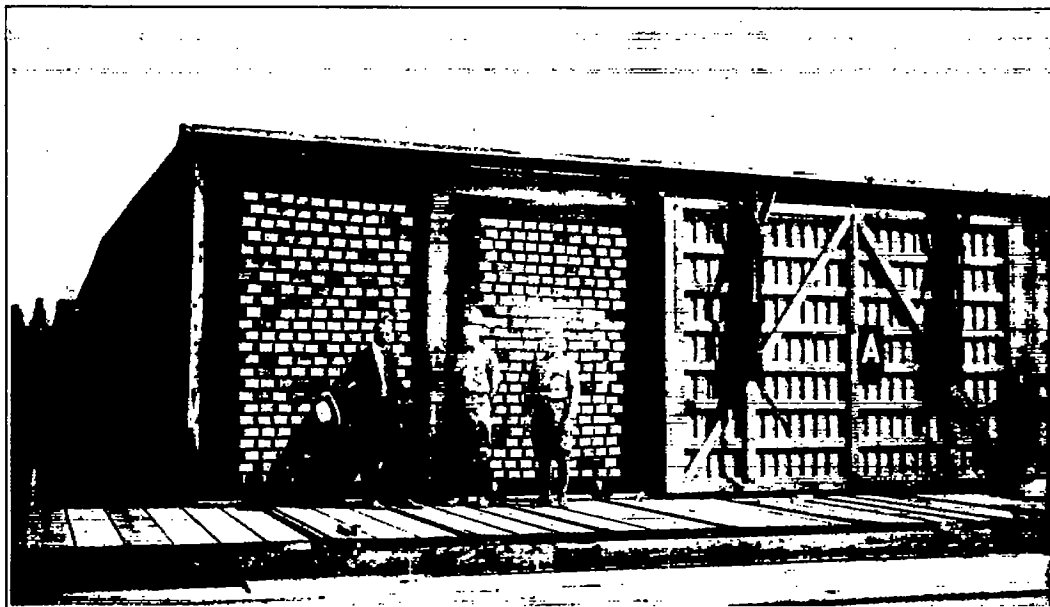
PLATE VIII.

FIG. 1.—ONE OF THE 24 WATER SPRAY DRY KILNS AT THE SIGNAL CORPS CUT-UP MILL, VANCOUVER, WASH., OPENED PREPARATORY TO UNLOADING; SHOWS METHOD OF PILING WING-BEAM STOCK.
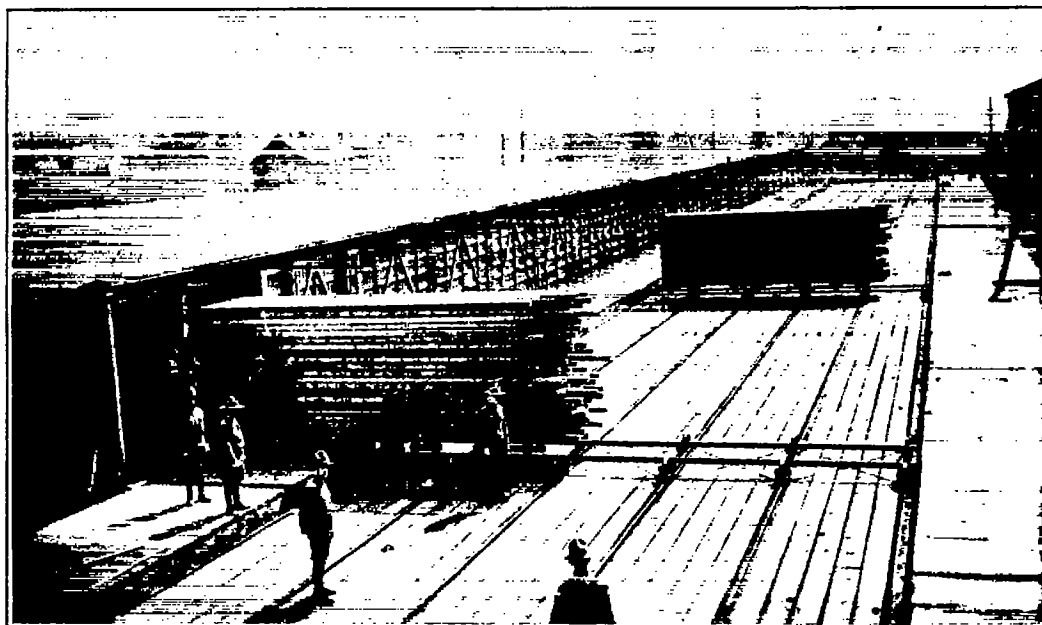

FIG. 2.—GENERAL VIEW OF THE BATTERY OF 24 WATER SPRAY DRY KILNS USED FOR KILN-DRYING WING-BEAM STOCK DURING THE WAR AT THE SIGNAL CORPS CUT-UP PLANT AT VANCOUVER, WASH.

VI. HOW TO CONDUCT THE DRYING OPERATION.

METHOD OF PILING.

In general lumber should be so piled as to afford free passage of the air throughout, and so that the air will pass through the pile and not around it. It is frequently advantageous to hang canvas curtains in such a manner as to prevent the air from short-circuiting the pile.

Remembering that the drying takes place progressively through the pile, it is evident that the pile should not be made too large, as otherwise what is gained in size will be lost in time of drying. This applies also to the question of how close together to place the sticks. If the pile is too crowded, the increased capacity will be lost in slowless of drying. Again, if the lumber is too openly piled the capacity of the kiln is unduly cut down without a compensating gain in time of drying. It is better to err on the side of too open rather than too close piling, since no harm will result other than loss in capacity, whereas too close piling may result in very uneven drying.

The greater the circulation in the kiln, the larger and closer may be the pile. For an ordinary condenser kiln without forced circulation it is generally desirable to allow about twice as much air space as solid lumber in the pile. Thus, for 3 by 4 inch wing-beam material 2-inch stickers and 2-inch spacings are preferable. Where high circulation is attainable this may be cut down to equal parts, or even to 6 parts solid to 5 parts open. Thus for 3 by 4 inch wing beams, 1 or 1¼ inch stickers with 1½ to 2 inch horizontal spacings may be used. For 1-inch boards 1-inch stickers should be used, when there is high circulation, and 1½-inch for low circulation.

In the water-spray kiln and in pipe condenser kilns the lumber should be run lengthwise of the kiln and the individual piles should not exceed 8 feet in height and 5 feet in width. An open flue of 18 inches should be left through the center of the kiln between the two 5-foot piles, and at least 12 inches between the lumber and the side walls.

A suitable method of piling wing-beam stock is illustrated in Plate VIII, which shows one of the kilns at the United States Signal Corps cut-up mill at Vancouver, Wash., opened for unloading. This kiln is loaded with 3 by 5 inch Douglas fir wing-beam stock.

Unless the drying takes place evenly from both surfaces of the boards there is a strong tendency for them to cup. Consequently the arrangement of the pile with respect to the movement of the air is of great importance from this point of view.

TESTS OF MATERIAL DURING AND AFTER DRYING.

For correct drying and the control of the whole operation it is essential to know currently the condition of the wood in various portions of the pile in regard to moisture, casehardening, and checking, as well as the temperatures, humidities, and air movements. Tests of the material must therefore be made as often as required. There are two means of acquiring this information; namely:

        (1) By the direct-test method.
        (2) By the sample-piece method.

The following tests are to be made:

        (1) Average moisture.
        (2) Moisture distribution.
        (3) Casehardening.

DIRECT-TEST METHOD.

One means of ascertaining this information is to pull out sticks of the wood from different places periodically and to test them for moisture and casehardening. Such tests must be made at a considerable distance (2½ or 3 feet) from the ends of the sticks, as otherwise they are liable to give erroneous conclusions due to the ends of the sticks having dried very much faster than the centers. It is frequently difficult if not impossible, however, to pull out representative material from the piles during the progress of the drying, and another method must be resorted to.

SAMPLE-PIECE METHOD.

This method can be best applied by preparing suitable sample pieces beforehand and inserting them into suitable pockets left in the sides of the piles when the lumber is first loaded. The samples should be representative material, cut from near the center of the chosen sticks and not less than 2½ feet in length. They should include some of the wettest as well as the average material, otherwise the load is likely to be considered dry before the wettest pieces have reached the required dryness. A 1-inch moisture disk should be taken from either end of the sample at the time of its preparation and immediately weighed on a delicate balance. The sample also should be weighed within a few minutes of the disks. The ends of the samples should then be thoroughly coated with thick asphaltum varnish, or be dipped in melted rosin 100 parts, lampblack 7 parts. The samples are then ready to be placed in the load in the pockets left for them. When samples are thus in place they should lie in exactly the same
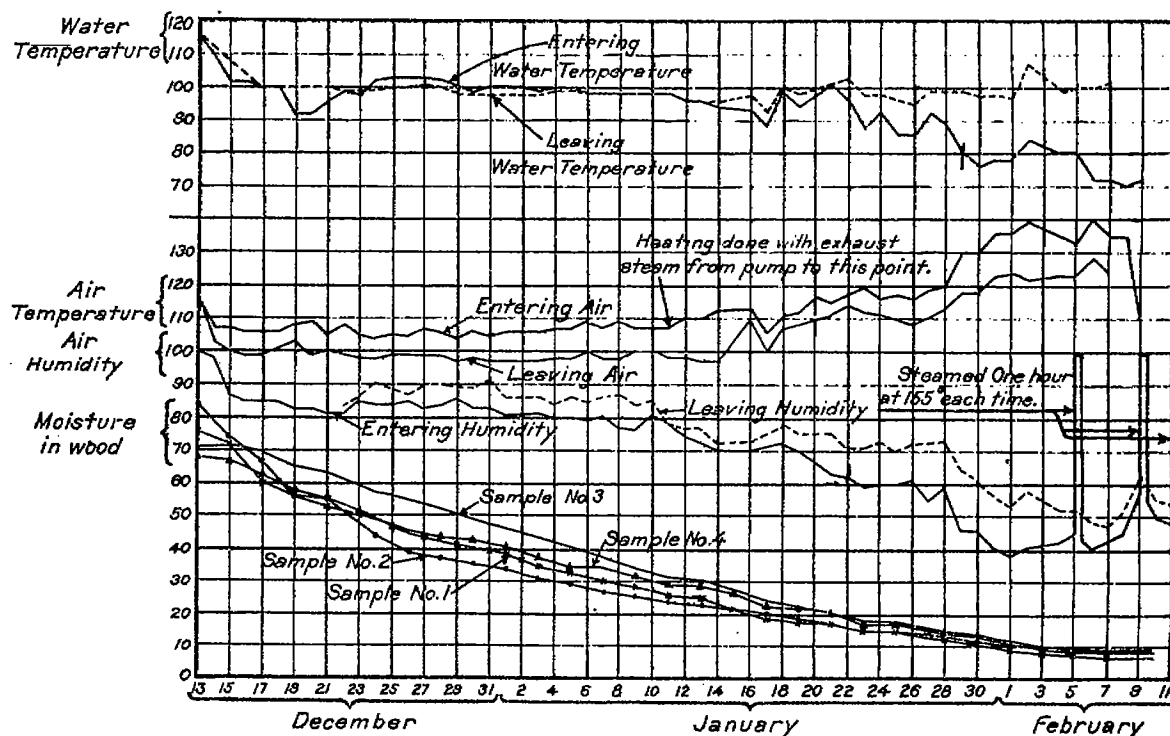
APPENDIX I.

FIG. 1.—DRYING RECORD OF RED AND WHITE OAK PROPELLER STOCK, SHOWING METHOD OF PLOTTING DATA AND KEEPING TRACK OF CONDITIONS.

relative positions as the other sticks in the pile, the ends being pieced out by the ends of the sticks from which they were cut and they must be readily accessible so that they can be re moved and replaced as often as desired. By first estimating the dry weights of the samples and then weighing them periodically during the drying run, the progress of the drying of the load may be kept track of currently.

How many samples to take will require judgment. They must be representative, but the more uniform and regular the drying conditions are in the kiln and the more uniform the material to be dried, the fewer will be required. Ordinarily at least four samples, two placed on the entering air side of the pile and two on the leaving air side, will be required, and frequently double this many.

Dry weight of the sample pieces is readily estimated as follows: Let A_1 and B_1 be the wet weights of the disks, A_0 and B_0 their oven dry weights. Let W_1 be the wet weight of the sample and W_0 its dry weight which is sought.

PLATE IX.
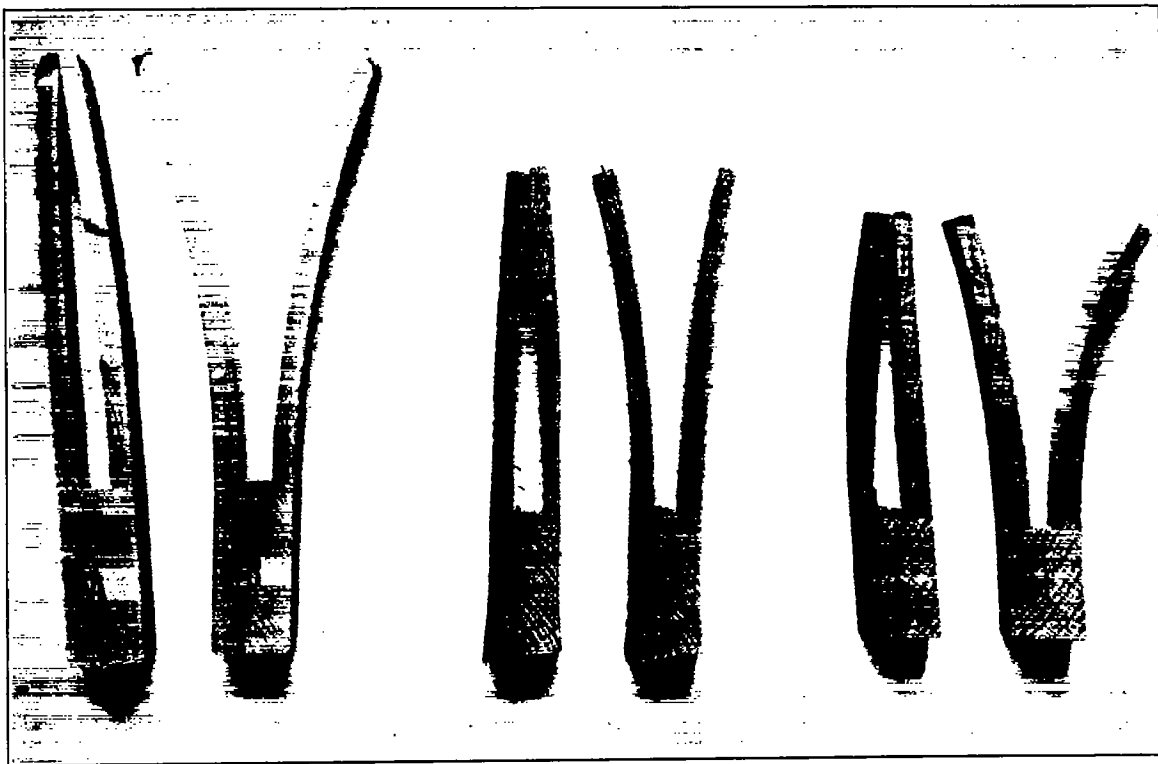
DISKS CUT FROM CASEHARDENED MAPLE AND OAK BOARDS,

The alternate ones on the left show the condition of the boards when first dried; those on the right show reversal of stresses brought about by steaming the same boards at a slight pressure.

$$\frac{(A_1+B_1)-(A_0+B_0)}{(A_0+B_0)}\times100=P_1$$ will be the original moisture per cent of the sample, in terms of oven dry weight. Then its dry weight W_0 will be

$$\frac{100\ W_1}{100+P_1}=W_0$$

If W_n be its current weight at any time, its moisture per cent will evidently be

$$\frac{W_n-W_0}{W_0}\times100=P_n$$

These current values should be plotted on cross-section paper in the form of curves showing the progress of drying; and the temperature, humidities, etc., should be also plotted on the same sheet, as shown in figure 1.

AVERAGE MOISTURE TEST.

The average moisture is determined by cutting a disk clear across the stick, far enough away from the ends to avoid the effect of end drying. One inch is a suitable thickness for this disk, but the exact thickness is immaterial. The disk should be weighed upon a sensitive balance immediately after cutting, before it has had time to lose or absorb any moisture from the air on the freshly cut surfaces. It is then to be dried in an oven, preferably at a temperature between 200° F. and 220° F., never above 230° F. When the disk has ceased to lose weight, which will require from one to two days' time for a wood like oak, it is again weighed. The loss in weight is the moisture content, and this quantity divided by the oven dry weight times 100 gives the "*moisture per cent*" as a standard, as determined by the equation for finding P_n, given above.

MOISTURE DISTRIBUTION TEST.

The moisture distribution disk should be sliced up into an outer layer $\frac{1}{4}$ inch thick and an inner core $\frac{1}{2}$ inch thick. The outer and inner parts should be weighed separately immediately, and their moisture content determined in the ordinary way, by drying in an oven at a temperature between 200° F. and 220° F., never above 230°.

CASEHARDENING TEST.

Casehardening as well as moisture distribution tests should be made from time to time. Two disks about $\frac{3}{4}$ inch in thickness should be cut, one of which is to be slotted in the longest direction so as to form two outer prongs, each $\frac{3}{8}$ inch thick, and two inner prongs of the same thickness, as shown in Plate IX. The slots should extend to within $\frac{3}{8}$ inch of the opposite side.

The indications of casehardening have been fully discussed elsewhere.

DRYING RECORDS.

The drying conditions can be best represented by means of a curve on cross-section paper, like those shown in the specifications in Appendix I. The temperatures and humidities in the curves are those of the air as it enters the pile of lumber; that is, in the flue in water-spray or condenser kilns or in places to be chosen as explained in the discussion of other kilns. The humidity will naturally be higher and the temperature lower where the air is leaving the pile on the sides, or at other portions of the pile. Records should be plotted currently in order to keep track of the progress of the drying operation.

TIME OF DRYING.

The time of drying will vary considerably in different kilns, depending upon the size and form of pile and the circulation. Since the run will be governed by that portion of the pile subjected to the most severe conditions, it necessarily follows that other portions will be relatively slower in drying; and if the air circulation is poor or the pile is very large or close, it may be necessary to continue to hold the final conditions for a considerable time after the material in the hottest portion has reached the proper condition for removal. The poorer the conditions of circulation, the longer will be the time required and the greater will be the discrepancy

in final moisture contents in different portions of the pile. It may even be desirable, in extreme cases of this kind, to raise the final humidity somewhat to prevent part of the stock from becoming too dry while the lagging material is drying down to the required condition. The time element of the drying curve is therefore not included in the specification given in Appendix I. Air-dried or partially dried material requires, of course, proportionally less time to dry. It is well to start with the drying conditions the same as for green material, but in a few days they may be reduced to those given on the curve corresponding to the actual moisture content of the wood.

As air-dried material is very apt to be casehardened it is generally desirable to begin with a preliminary steaming treatment at about 160° for 24 hours in order to remove the surface stress and to remoisten the outer surface. Immediately after the steaming, the temperature and humidity should be reduced to those used at the start—120° and 80 per cent for spruce, for example.

REMOVAL OF CASEHARDENING.

Casehardening, if it develops, may be removed by a steaming treatment at 170° or 180° for ½ to 1½ hours, according to requirements, either during the drying or at the end of the run, a day or so before removal from the kiln. Oak, however, should be steamed at lower temperatures, not over 160°. This may be accomplished by turning boiler pressure steam into perforated steam pipes properly arranged for the purpose. The $\frac{1}{16}$-inch holes should be about 6 inches apart and so placed as to produce a high circulation through the pile of lumber.

Another means of accomplishing this result is to raise the humidity considerably at the end of the run without raising the temperature, thus allowing the outer surface to reabsorb moisture. This relieves the set condition and allows normal shrinkage to be resumed.

Which method is the best to use will have to be determined by the operator to suit the special conditions and species of the material.

MOLD.

Mold is likely to form on some woods, especially green oak and walnut, during the first part of the operation. Aside from retarding the circulation it does not injure the stock, but it must not be allowed to develop. It may be removed by steaming for half an hour or so at 160° F. or over, providing the circulation is sufficient to carry this temperature well through the pile.

APPENDIX I.

DRYING SPECIFICATIONS FOR AIRPLANE STOCK.

At the beginning of the war, the Forest Service was already in possession of knowledge, derived from years of experimental study, to enable it to offer immediately a method by which it was believed that kiln drying could be accomplished without injury to the material. The Forest Service was in a better position than any other organization or individual to recommend suitable methods and apparatus for drying airplane stock. Drying specifications were prepared for the Signal Corps, based on the knowledge and experience then available. They were first drawn on July 2, 1917, and have been employed without significant changes.

The necessity for establishing beyond question the safety of the original drying conditions given in these specifications, however, was apparent, as well as the need to ascertain their application to untried species and to establish limiting conditions as to severity of treatment beyond which it would be unsafe to go. This called for an exhaustive series of strength tests upon material which had been kiln dried under different conditions and a comparison not only with matched green specimens, but likewise with matched specimens which had been set aside and air dried under most favorable conditions. The investigation which was undertaken immediately by the Madison Laboratory of necessity required considerable time before definite conclusions could be drawn, since the matched samples had to become thoroughly air dry. Tests are still in progress, but sufficient results have now been obtained to establish for a certainty the safety of the conditions prescribed in the original specifications prepared in July, 1917. These results are reported in the monograph entitled "The Effect of Drying on the Strength of Airplane Woods."

The following is the specification as finally slightly modified and adopted by the Signa Corps:

[Signal Corps, United States Army.]

SPECIFICATION FOR GENERAL KILN-DRYING PROCESS FOR AIRPLANE STOCK.

[Nos. 20500 and 20500-A.]

GENERAL.

1. This specification covers the general requirements of the Signal Corps for kiln-drying of wood for airplane stock.

2. The kiln-drying operations shall be so conducted that the wood will not lose any strength, toughness, or other physical property.

MATERIAL.

3. Only one species and approximately one thickness shall constitute a kiln charge. A difference of not to exceed ¼ inch in thickness of single pieces will be allowed.

PILING.

4. The boards shall be piled so that the horizontal width of the spaces between them will be at least 1 inch for each inch of board thickness, but in no case shall the horizontal width of such spaces exceed 3 inches. The boards must be held flat and straight while drying.

5. For stock up to 4 quarters (1 inch) in thickness, the crossers shall be at least 1 inch thick and not over 1½ inches wide.

6. For stock from 4 to 12 quarters (1 to 3 inches) in thickness, the crossers shall be at least 1½ inches thick and not over 1½ inches wide.

7. For stock over 12 quarters (3 inches) in thickness the thickness of the crossers shall be increased in the above proportion but must not exceed 2 inches in any case.

8. The crossers shall be placed directly over one another and not over 3 feet apart in the courses.

9. The lumber must be so disposed in the kiln as to permit of easy access on both sides of the pile and the taking of temperature and humidity readings whenever required by the inspector.

INSTRUMENTS.

10. At least one recording thermometer or recording hygrometer of approved make shall be used in each dry kiln compartment.

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11. Recording thermometers or hygrometers shall be checked at least once every kiln charge, with a standard thermometer or a glass thermometer calibrated to an accuracy of 1° F. This comparison shall be made with the thermometers placed so as to record the maximum temperature of any portion of the pile.

12. *Thermometers.*—Thermometer bulbs must be shielded from direct radiation of steam pipes, wet lumber, cold walls or surfaces, and must receive a free circulation of air.

13. The inspector may, at his discretion, place other thermometers at any point in the pile.

14. *Hygrometer.*—Humidity readings shall be made at least three times daily or more often as the inspector may desire, according to standard methods approved by the inspector, at the same points where the recording thermometers or hygrometer bulbs are placed.
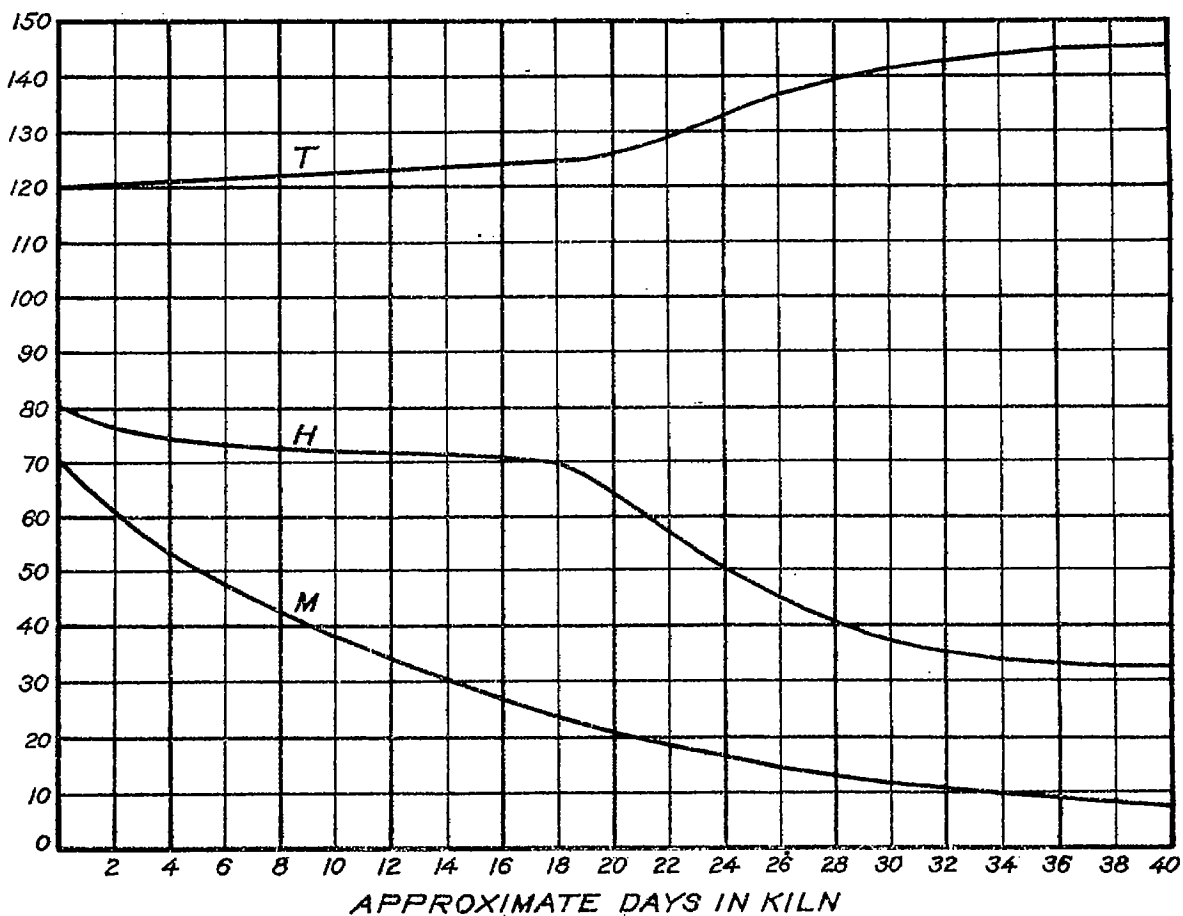
APPENDIX I.

FIG. 2.—SPECIFICATION SCHEDULE, TABLE 1, FOR AIRPLANE WING-BEAM STOCK. T, TEMPERATURE F.; H, RELATIVE HUMIDITY, PER CENT; M, NORMAL DRYING CURVE, PER CENT OF MOISTURE; ALL ON ENTERING AIR SIDE OF PILE OF LUMBER.

15. The following shall constitute a standard method: Use a glass or recording wet and dry bulb hygrometer with distilled water and with the wick changed at least once a week; produce a circulation of air past the wet bulb of at least 5 feet per second before reading.

16. Hygrometer bulbs must be shielded from direct radiation of steam pipes, wet lumber, cold walls or surfaces, and must receive a free circulation of air.

STEAMING.

17. *At the beginning of the drying operations.*—Green wood is to be steamed at a temperature not to exceed 15° F. higher than the initial drying temperature specified in Tables 1 and 2, for 6 hours for each inch of thickness. Humidity during steaming period must be 100 per cent, or not below 90 per cent, in every portion of the pile.

18. Previously air-dried wood is to be steamed at a temperature not to exceed 30° F. higher than the initial drying temperature specified in Tables 1 and 2, for 8 hours for each inch of thickness. Humidity during steaming period must be 100 per cent, or not below 90 per cent in every portion of the pile.

19. *Near the end of the drying.*—If on official test the stock shows serious casehardening it shall be steamed at a temperature not to exceed 20° F. higher than the final drying temperature specified in Tables 1 and 2, for not more than 3 hours. After steaming it shall be redried.

TEMPERATURE AND HUMIDITY.

20. Operating conditions are specified in Tables 1 and 2, but lower temperatures and higher humidity conditions are permissible.

21. The progression from one specified stage to the next must proceed without abrupt changes.

22. *Green wood (above 25 per cent moisture) over 3 inches thick.*—Reduce the temperature values given in Tables 1 and 2 by 5° F. for each inch increase in thickness.

23. *Air-seasoned wood (below 25 per cent moisture) over 3 inches thick.*—Reduce the temperature values given in Tables 1 and 2 by 5° F. for each inch increase in thickness.

TABLE 1.

Stage of drying.	Drying conditions.	
	Maximum temperature, Fahrenheit.	Minimum relative humidity, per cent.
At the beginning	120	80
After fiber saturation is passed (25 per cent)	125	70
At 20 per cent moisture	128	60
At 15 per cent moisture	138	44
At 12 per cent moisture	142	38
At 8 per cent moisture	145	33
Final	145	33

24. Table 1 applies to the following woods:

Ash, white, blue, and Biltmore.
Birch, yellow.
Cedar, incense.
Cedar, northern white.
Cedar, western red.
Cedar, Port Orford.

Spruce, Sitka.
Cypress.
Pine, sugar.
Pine, white (Idaho or eastern).
Spruce, eastern (red or white).
Douglas fir.

TABLE 2.

Stage of drying.	Drying conditions.	
	Maximum temperature, Fahrenheit.	Minimum relative humidity, per cent.
At the beginning	105	85
After fiber saturation is passed (25 per cent)	110	73
At 20 per cent moisture	117	62
At 15 per cent moisture	129	46
At 12 per cent moisture	135	42
At 8 per cent moisture	135	40
Final	135	40

25. Table 2 applies to the following woods:

Cherry.
Mahogany.
Oak, white and red.

Walnut, black.
Maple.

TESTS DURING DRYING.

26. Samples shall be inserted in the pile in such manner that they will be subjected to the same drying conditions as that portion of the pile where inserted. They shall be so placed

that they can be removed for periodical weighing in order to ascertain the average moisture content of the pile at any time.

27. Three samples shall be used for each 10,000 board feet or less of material in the pile. Each sample is to be 2 feet long and shall not be cut nearer than 2 feet to the end of one of the pieces to be dried.

28. The original moisture content of the samples shall be determined from sections 1 inch

APPENDIX I.

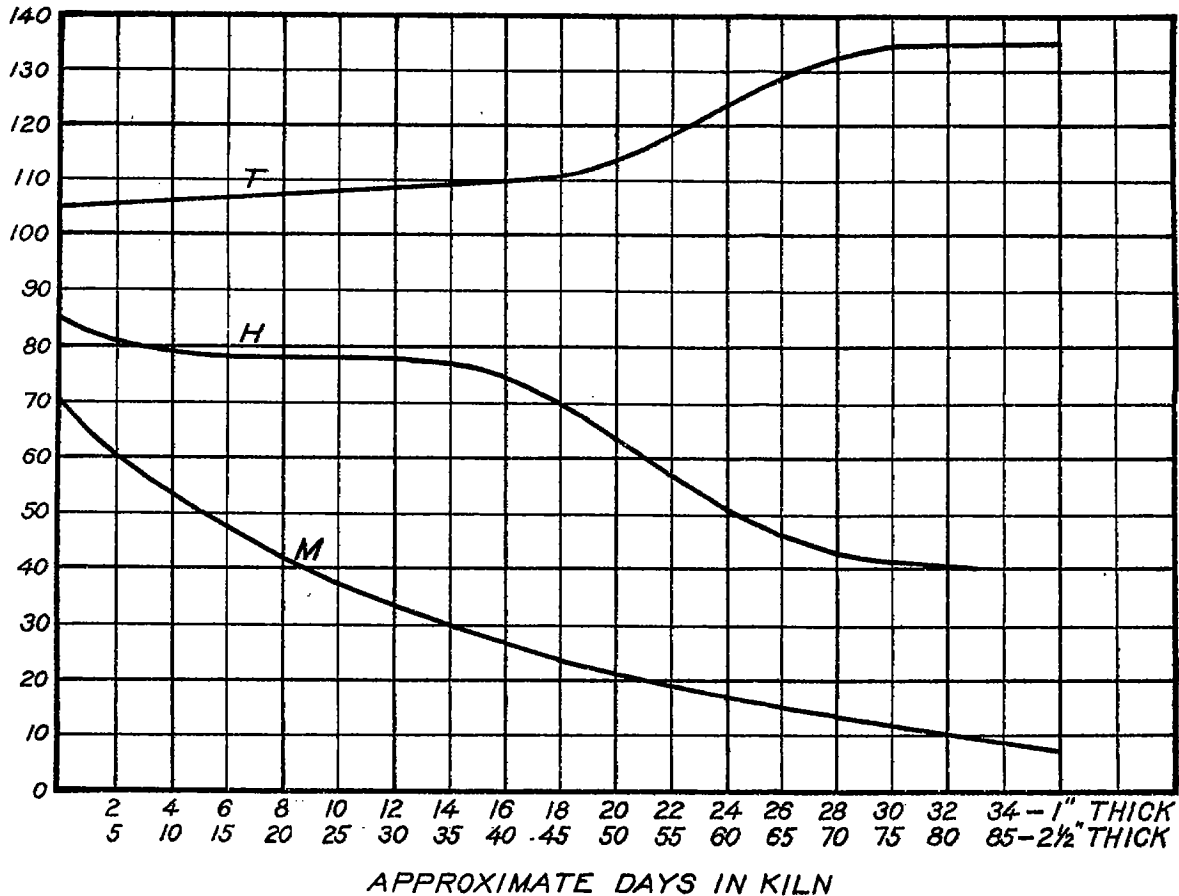

APPROXIMATE DAYS IN KILN

FIG. 3.—SPECIFICATION SCHEDULE, TABLE 2, FOR PROPELLER STOCK AND HARDWOODS.

Nomenclature as in figure 2.

thick cut from both ends of the sample at the time it is sawed from the stick. This determination shall be made as provided in specification No. 20504–A.

29. Before placing them in the pile, the ends of the samples must be given a thorough coating of asphaltum varnish to prevent end drying.

30. The samples shall be weighed to an accuracy of one-tenth of 1 per cent immediately after cutting the moisture sections and before placing in the kiln. They shall be weighed at least daily when the time of drying is 10 days or less, and at least every other day when the time of drying is more than 10 days.

31. The samples shall be placed in the pile and distributed so that they will be exposed to the average, most rapid, and slowest drying, except that they shall not be placed on the top or bottom layers. The samples placed in the portion of the pile where drying is most rapid shall control the regulation of the temperature and humidity.

32. After obtaining the dry weight of the samples, the average moisture condition of the pile during the drying shall be determined after each weighing.

33. The following example will illustrate the method employed:

Original weight of sample = 7.35 pounds.
Original moisture per cent (average of the two 1-inch sections) = 47.
Calculated dry weight of sample = 7.35 divided by 1.47 = 5.00 pounds.
Current weight = 6.23 pounds.
Moisture in samples = 6.23 − 5.00 = 1.23 pounds.
Current moisture per cent = (1.23 divided by 5.00) × 100 = 24.6.

34. Continuous and permanent records must be kept of the temperature and humidity observations and the percentage of moisture in the lumber in the kiln.

TESTS AFTER DRYING.

35. Standard moisture content and casehardening tests shall be made before the lumber is removed from the kiln. Material for these tests shall be taken from four boards for each 5,000 board feet or less of material in the pile. Pieces selected must fairly represent the dried stock and shall be taken from different parts of the pile. At his discretion the inspector may select other pieces for tests. Sections for these tests shall not be cut nearer than 2 feet to the ends of the pieces.

36. Three adjacent sections, 1 inch thick, shall be cut from the centers of each test piece of stock. Each section must be weighed within five minutes to prevent moisture evaporation.

37. *The first section.*—(A, fig. 4) shall be dried whole and the average moisture content obtained as provided in specification No. 20504–A.

38. *The second section.*—(B, fig. 4) moisture distribution section shall be cut into an outer shell ¼ inch wide and an inner core ½ inch wide. The moisture content of the outer shell and inner core shall be determined.

39. *The third section.*—(C, fig. 4) shall be sawed parallel to the wide faces of the original board into tongues or prongs, leaving about ½ inch of solid wood at one end of the section. For material less than 2 inches thick two saw cuts shall be made and for material more than 2 inches thick five saw cuts shall be made. In sections having six prongs the second prong from each side shall be broken out, leaving two outer and two central prongs. The center prong shall be removed from sections having only three prongs.

40. The third section shall then be allowed to dry for 24 hours in the drying room and any curving of the prongs noted.

41. If the prongs remain straight, perfect conditions of stress and moisture content are indicated.

42. If the outer prongs bend in, conditions of casehardening are indicated.

43. Only very slight casehardening is permissible.

FINAL MOISTURE CONDITIONS.

44. An average dryness of approximately 8 per cent, unless otherwise specified, shall be required. A moisture content of from 5 to 11 per cent is permissible in individual sticks.

45. The variation in moisture content between the interior and exterior portions of the wood, as shown by the "moisture distribution section" provided for in paragraph 38, must not exceed 4 per cent.

SEASONING.

46. Before manufacture the wood shall be allowed to remain in a room, with all parts under uniform shop conditions, at least two weeks for 3-inch material, and other sizes in proportion.

STEAMING AND BENDING OF ASH FOR LONGERON CONSTRUCTION.

47. The ash shall be cut in the form of rough squares sufficiently large to allow for shrinkage and finish.

48. Where it is necessary to bend this material, it shall be steamed in the green condition (more than 18 per cent moisture), bent on forms, and then kiln dried as provided in paragraph 23.

49. Steaming shall be conducted at a temperature not to exceed 212° F. for a period not longer than six hours, and the bending shall be accomplished while the material is hot.

INSPECTION.

50. At all stages of the process the lumber shall be subject to inspection by the Inspection Department of the Signal Corps under its Manual of Inspection.

APPENDIX I.

SECTION A

TO BE WEIGHED, THEN OVEN-DRIED, THEN REWEIGHED TO DETERMINE AVERAGE MOISTURE CONTENT OF PIECE.

SECTION B
OUTER MARGIN SAWED OR SPLIT OFF AS SHOWN.

$\frac{1}{4}$TH. THICKNESS OF PIECE.

OUTER PORTION   INNER PORTION

OUTER AND INNER PORTION WEIGHED, DRIED AND REWEIGHED SEPARATELY TO DETERMINE DIFFERENCE IN MOISTURE CONTENT.

SECTION C
THICK STOCK SAWED AS SHOWN FOR CASEHARDENING TEST, PRONGS 2 AND 5 TO BE BROKEN OUT.

SECTION TO BE DRIED BEFORE CONCLUSION AS TO CASE HARDENING IS MADE.

NOT CASE HARDENED   CASE HARDENED NOT PERMISSIBLE IN AIRPLANE STOCK   SHOWING EFFECT OF OVERSTEAMING
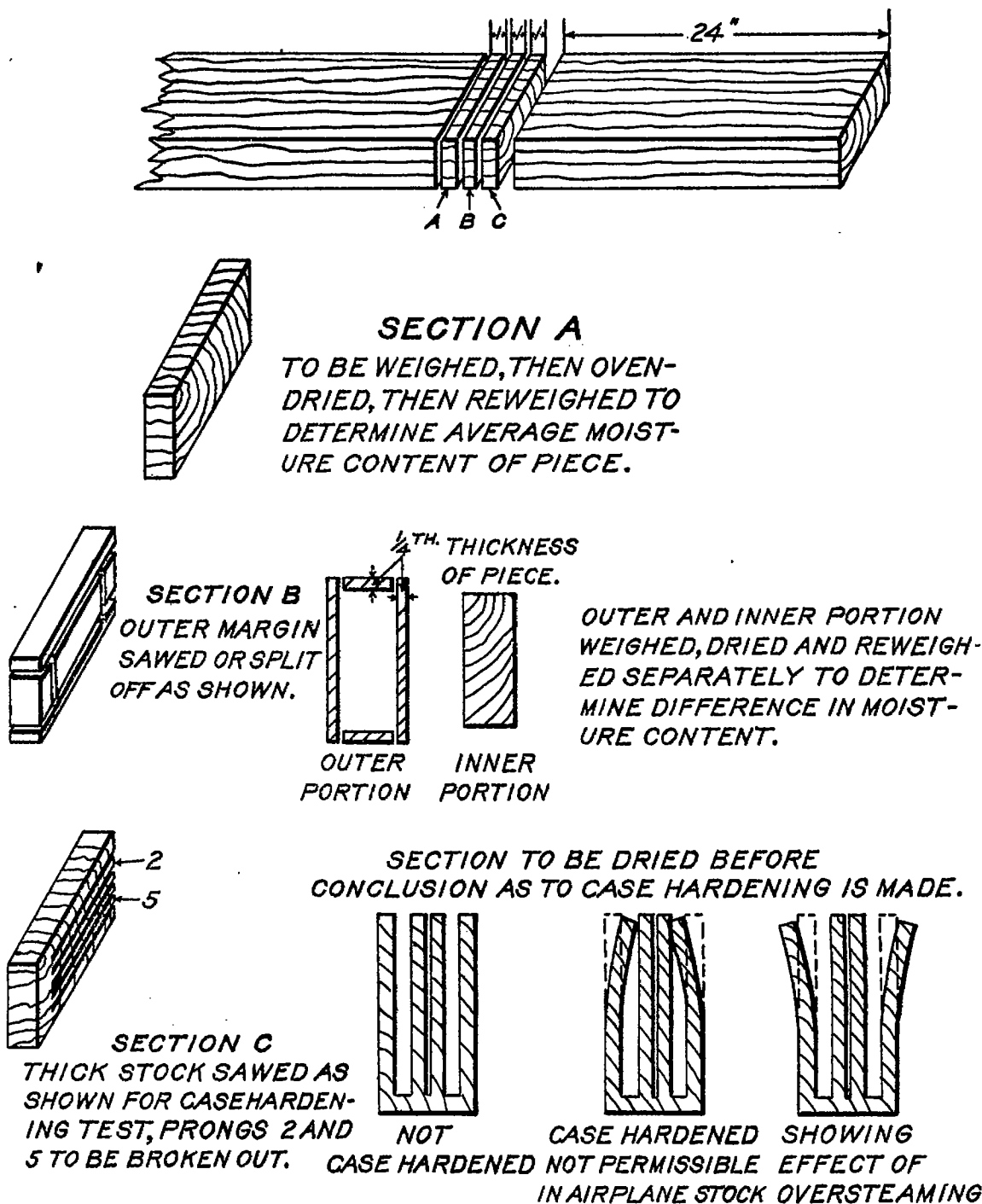
FIG. 4.—SPECIFICATION NO. 20500-A, MOISTURE AND CASEHARDENING TEST SPECIMENS.

51. The inspector shall mark all lumber with the official acceptance or rejection symbol of the Signal Corps.

52. The inspector shall have free access to every part of the kiln at all times and shall be afforded every reasonable opportunity to satisfy himself that this specification is being complied with.

APPENDIX II.

CONSTANT DEW-POINT SCHEDULE FOR DRYING DOUGLAS FIR, SPRUCE, AND SIMILAR WOODS

An improvement over the schedule in the original specifications for drying species listed under Table I of Signal Corps, United States Army, specification 20500–A, was worked out, by the use of a constant dew point of 115°, and is shown in Plate III. This somewhat simplifies the control of the operation, especially in the water-spray kilns, where the dew point is used as the controlling element of the humidity. The schedule here given is equally good with the former, and has already been put into use.

If marked casehardening becomes apparent it should be removed by steaming for two or three hours at 160° once or twice near the end of the run, as indicated by "S" in the plate of curves. If no very severe casehardening develops, a high humidity for one day just before the close of the run, without raising the temperature, may suffice. Steaming at a temperature of 160° for not over one hour should always be resorted to if severe casehardening develops at any stage of the run, but is not ordinarily necessary if the given schedule be adhered to.

In figure 5, T is the temperature of the air entering the pile of lumber, in degrees Fahrenheit, D is the dew point, H is the relative humidity per cent, and M is the normal drying curve of the lumber on the entering air side of the pile, in percentage of the dry weight.
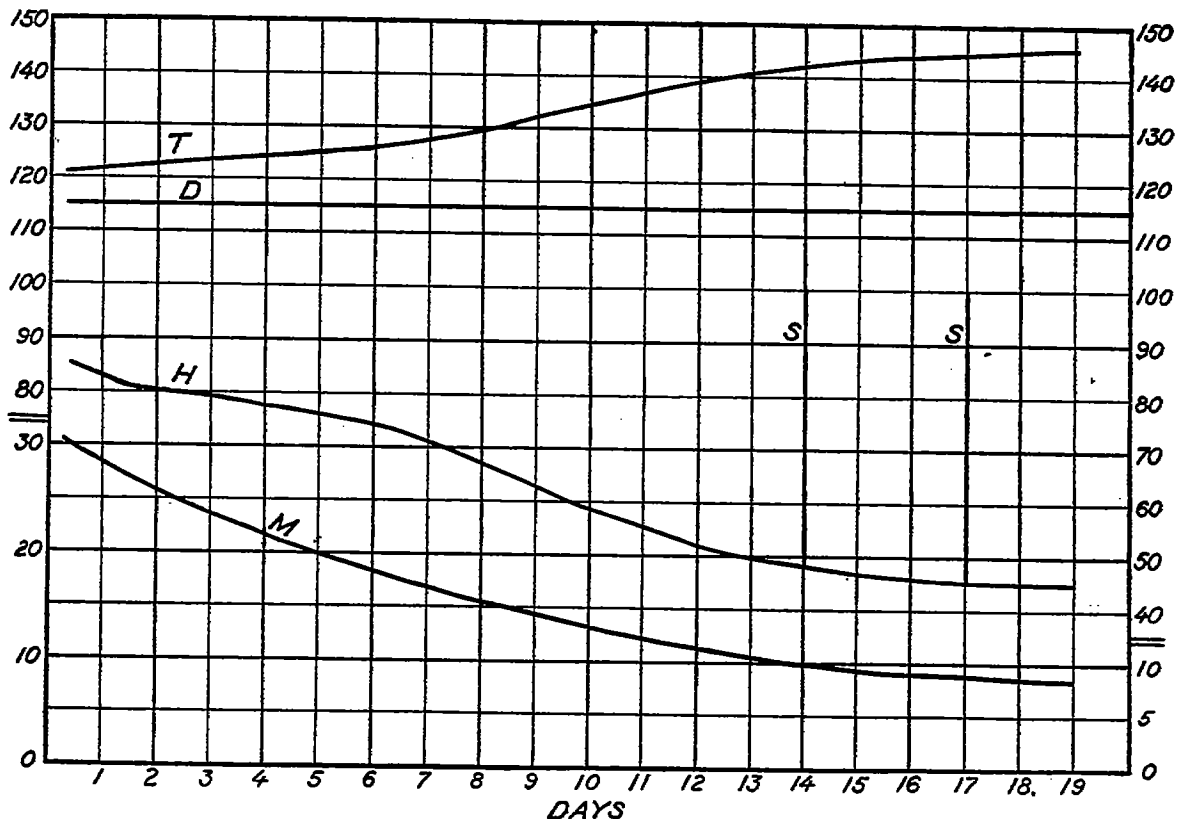
APPENDIX II.

FIG. 5.—CONSTANT DEW-POINT SCHEDULE FOR AIRPLANE WING-BEAM STOCK MAY BE USED IN PLACE OF TABLE I SCHEDULE, WITH EQUALLY GOOD RESULTS.

APPENDIX III.

THE FOREST SERVICE WATER-SPRAY KILN.

In figure 6 is shown the cross section of a Forest Service water-spray kiln which has proved successful in drying airplane stock.[1] While airplane woods can be satisfactorily dried in
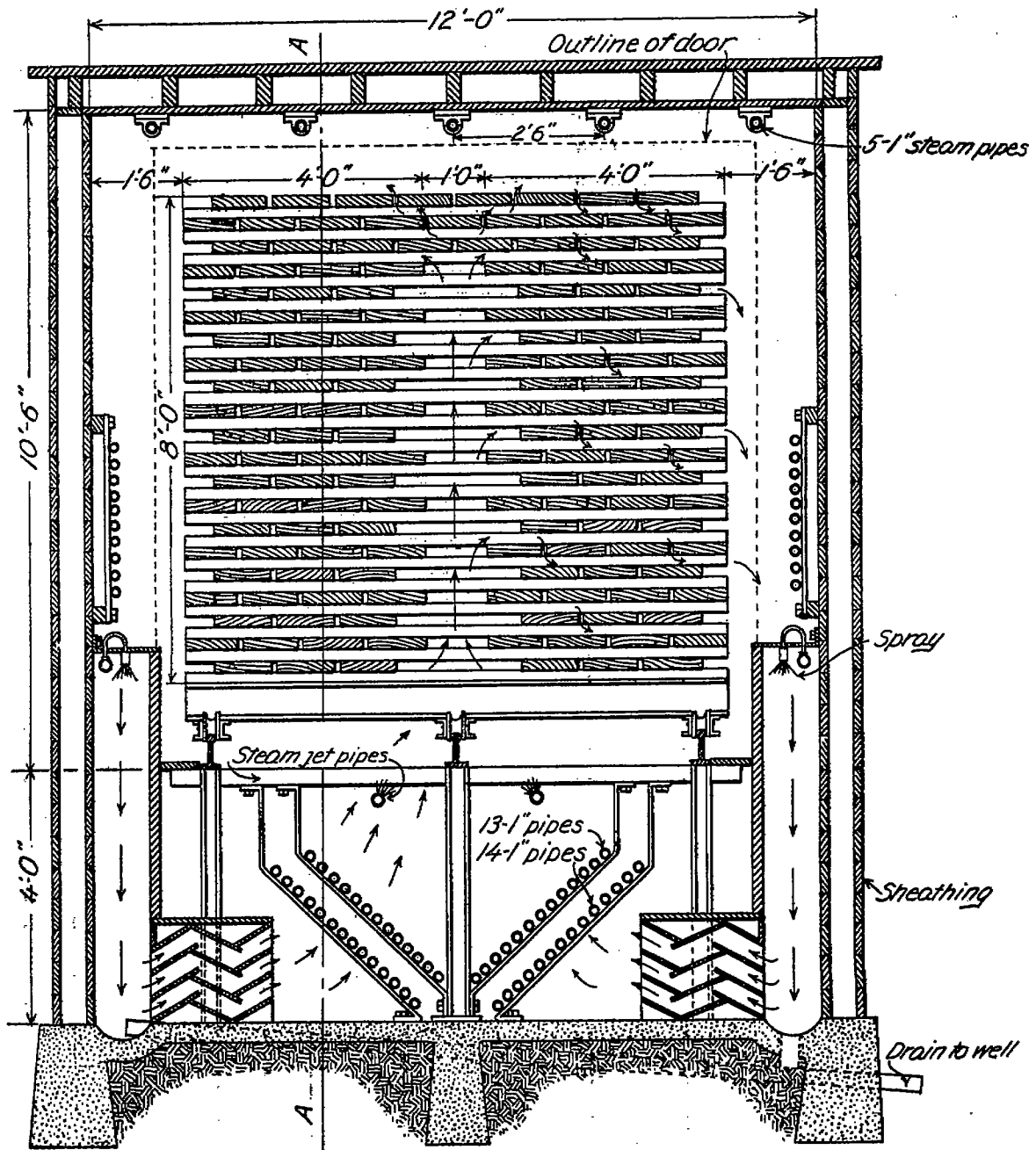
FIG. 6.—DIAGRAMMATIC CROSS-SECTIONAL VIEW OF THE WATER SPRAY DRY KILN.

various forms of kilns, the water spray is recommended for the purpose on the basis of considerable experience. Since many of these are already in use for this purpose only a brief description will be given.

The essential feature of this kiln is control of the humidity and the production of air circulation by means of a series of water sprays, spaced short distances apart and running the entire length of the kiln and operating in narrow flues about 12 to 16 inches in width and about 6 feet deep.

One flue is placed on either side of the kiln, as shown in figure 6; or a single flue may be placed in the center. The spray of water is directed downward with considerable force, and produces a large movement of air, which, after leaving the baffle plates at the bottom of the spray chambers, rises through the heating coils and upward through the central flue between the piles of lumber; thence it passes downward and outward to the spray flues again.

The humidity is regulated by the temperature of the spray water, the air being brought to a condition of complete saturation in its passage through the sprays of water. Cold water reduces humidity and hot water raises it, since the temperature of the air as it leaves the bottom of the spray chambers is the dew point of the air after it is heated in passing through the heating pipes. Thus, the humidity of the air delivered to the lumber is controlled by controlling the dew-point temperature.

Zigzag baffle plates are arranged at the bottom of the spray chambers to remove all free particles of water and leave the air in a clear saturated condition as it enters the steam pipes. Condensers are also placed above the spray chambers, to be used near the end of the run when a low humidity but not much air circulation is required, and a high-pressure steam spray pipe is placed in the spray chambers for use in relieving casehardening. There are no ventilators, and the kiln is tightly closed, the same air being recirculated over and over.

Only these essential parts need be mentioned here, since in this brief discussion a complete design of the kiln is not intended and the planning of new kilns or the modification of old ones would need to be taken up in detail according to requirements.

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[1] This kiln has been patented by the author and dedicated to the public, No. 1019743, Mar. 5, 1912; No. 1019999, Mar. 12, 1912; and No. 1228989 June 5, 1917.

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